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The Journal of
THE ROYAL AERONAUTICAL SOCIETY

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APRIL 1948 NO 448 VOL. 52

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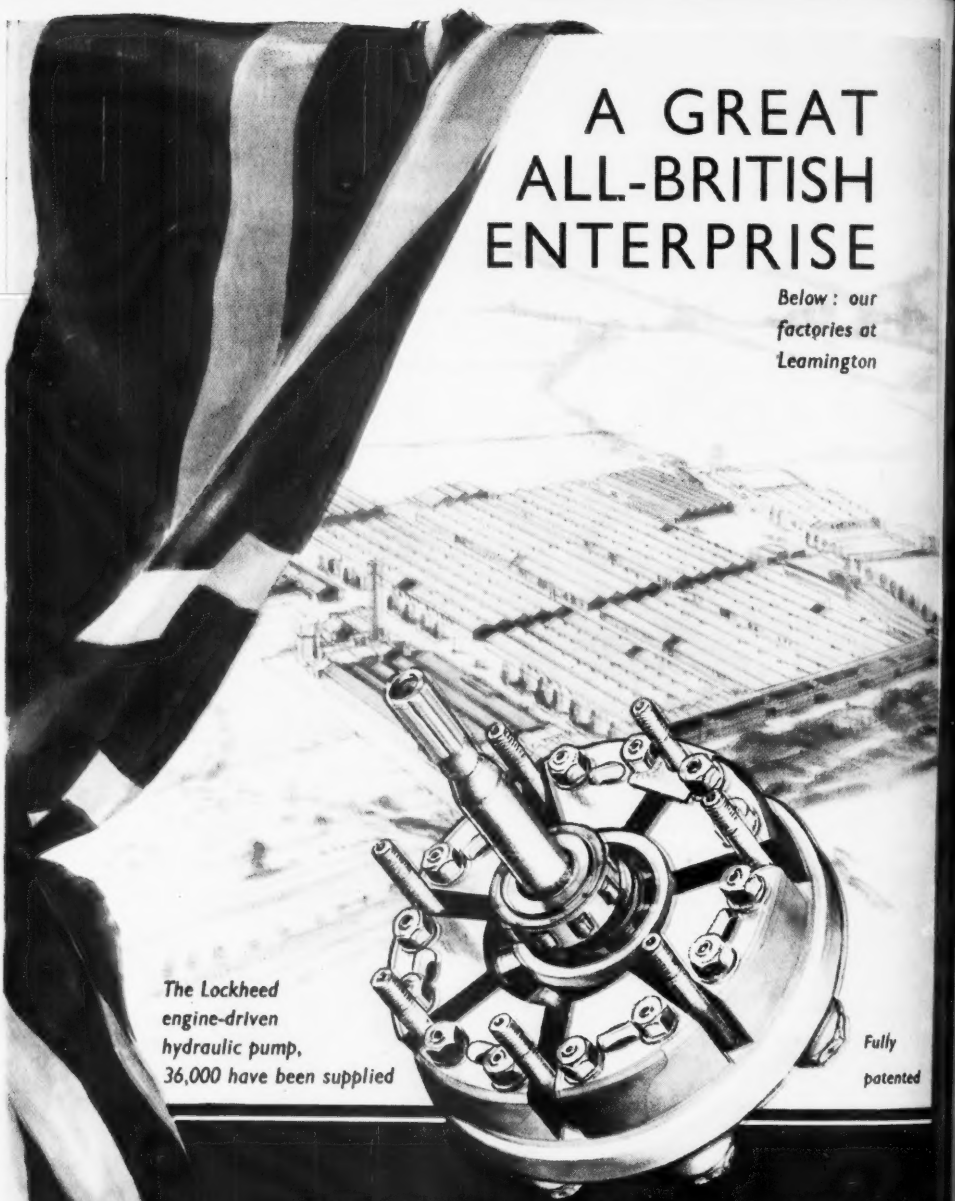

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APRIL NOTICES 1948

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.

CONTENTS OF THE APRIL JOURNAL

The Third British Commonwealth and Empire Lecture: Aircraft and the Airlines —A Canadian View, by James T. Bain.

The Work of the High Speed Tunnel, by Professor A. Thom, M.A., D.Sc., and W. G. A. Perring, F.R.Ae.S.

Delays in the Flow of Air Traffic, by E. G. Bowen, M.Sc., Ph.D., O.B.E., and T. Pearcey, A.R.C.S.

ANNUAL GENERAL MEETING

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Friday, 7th May 1948, at 6.0 p.m., in the offices of the Society, 4 Hamilton Place, London, W.1.

AGENDA

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets of Aerial Science Limited and Aeronautical Trusts Limited for the year ended 31st December 1947.
3. To receive the names of those elected to Council for the years 1948-1951.
4. To announce the List of Fellows elected by the Council in accordance with Rule 4.
5. To elect the Auditors for the ensuing year for Aerial Science Limited and Aeronautical Trusts Limited.
6. Any other business.

By Order of the Council,
J. LAURENCE PRITCHARD,
Secretary.

Light refreshments will be served before the Meeting at 5.30 p.m.

DONATIONS

The Council gratefully acknowledge the gift to the Society of £300 for seven years from Sir George Nelson, Chairman and Managing Director of the English Electric Company. This most generous gift has been earmarked for the technical work of the Society and the preparation of data sheets and monographs.

WILBUR WRIGHT MEMORIAL LECTURE

The title of the 36th Wilbur Wright Memorial Lecture, to be read on 27th May by Mr. A. Gouge, B.Sc., F.R.Ae.S., will be: Size in Transport. A review of the development of the subject, with particular respect to size and the application of its lessons to Air Transport.

MEDALS AND AWARDS

The following medals have been awarded by the Council. They will be presented at the Wilbur Wright Memorial Lecture to be held on 27th May 1948.

Society's Gold Medal

The Society's Gold Medal, the highest honour the Society can confer, has been awarded to Professor Sir Bennett Melvill Jones, C.B.E., A.F.C., F.R.S., Hon.F.I.Ae.S., F.R.Ae.S., for his outstanding work in Aerodynamics.

Society's Silver Medal

Awarded for some advance in aeronautical design, to I. I. Sikorsky for his work on the development of the Helicopter.

Society's Bronze Medal

Awarded for some advance in aeronautical design, to Miss F. B. Bradfield, O.B.E., M.A., F.R.Ae.S., for her work on aeronautical research.

Simms Gold Medal

Awarded annually for the best paper read in any year before the Society on any science allied to aeronautics such as meteorology, wireless telegraphy, instruments, and so on, to Sir William T. Griffith, D.Sc., F.R.I.C., F.Inst.P., F.I.M., for his paper "The Problem of High Temperature Alloys for Gas Turbines."

George Taylor (of Australia) Gold Medal

Awarded for the most valuable paper submitted or read during the previous session, to Dr. J. W. Drinkwater, B.Sc., Wh.Sc., and W. G. Glendinning, B.A., A.F.R.Ae.S., for their paper on "The Risk of Fire and Fire Prevention Methods."

Edward Busk Memorial Prize

Awarded for the best paper received on some subject of a technical nature connected with aeroplanes, to Air Marshal the Hon. Sir Ralph Cochrane, K.B.E., C.B., A.F.C., for his paper on "The Development of Air Transport During the War."

R.38 Memorial Prize

Awarded for the best paper on some subject of a technical nature in the science of aeronautics, to W. M. Widgery, F.R.Ae.S., for his paper on "Pressurisation of Aircraft."

Branch Prize

Awarded for the best paper on an aeronautical subject read before the Branches of the Society jointly to, A. N. Clifton, F.R.Ae.S., for his paper on "Naval Aircraft" read before the Southampton Branch, and J. A. Kirk for his paper on "Wind Tunnels" read before the Belfast Branch.

JOURNAL PREMIUM AWARDS

The Council have made the following premium awards for 1947 for papers published in the Journal:—

R. K. Page, B.Sc., A.F.R.Ae.S., Performance Calculation for Jet-Propelled Aircraft. Twenty pounds. May 1947 Journal.

Professor F. Panlilio, The Theory of Limit Design applied to Magnesium Alloy and Aluminium Alloy Structures. Twenty pounds. June 1947 Journal.

P. B. Walker, M.A., Ph.D., F.R.Ae.S., Mechanical Vibration and Aeroelasticity. Fifteen pounds. April 1947 Journal.

Lt. (A) (A/E) T. E. G. Bowden, R.N., Grad.R.Ae.S., Design for Maintenance. Ten pounds. March 1947 Journal.

W. Tye, B.Sc., F.R.Ae.S., Gusts. Ten pounds. September 1947 Journal.

F. W. Morgan, B.Sc., A.R.Ae.S., High Speed Aircraft Flying Limitations and Handling Problems. Ten pounds. September 1947 Journal.

L. Malavard, The Use of Rheo-electrical Analogies in Certain Aerodynamical Problems. Ten pounds. September 1947 Journal.

L. W. Rosenthal, A.F.R.Ae.S., The Influence of Aircraft Gross Weight upon the Size and Weight of Hulls and Fuselages. Ten pounds. November 1947 Journal.

M. J. Kemper, M.B.E., A.R.Ae.S., Maintenance Difficulties in the Field. Ten pounds. December 1947 Journal.

LOUIS BLERIOT LECTURE

The first Louis Bleriot Lecture, which has been instituted by the Association Française des Ingènieurs et Techniciens de l'Aéronautique, will be given in Paris on the 12th May 1948. The lecture, " The Art of the Aviation Engine," will be given by Air Commodore F. R. Banks, C.B., O.B.E., M.I.Aut.E., F.I.P., M.S.A.E., M.I.Mech.E., F.R.Ae.S. The lecture will be in French and will be read on behalf of Air Commodore Banks by Colonel Guy du Merle,. C.R.D.

A.F.I.T.A. has extended a warm invitation to members of the Society to attend the lecture.

NORTHERN HEIGHTS MODEL FLYING CLUB

The Northern Heights Model Flying Club will hold a gala day at Langley Aerodrome, Slough, on Sunday, 20th June 1948, through the courtesy of the Directors of Hawker Aircraft. In addition to the many well established trophies, competitions for the Queen's Cup and the Helicopter Trophy will be held for the first time.

Members of the Society will be welcomed.

Details of contests and particulars of routes to the aerodrome may be obtained from the Hon. Secretary, Northern Heights Model Flying Club, H. R. Turner, 61 Avenell Road, Highbury, London, N.5.

S.B.A.C. SCHOLARSHIPS

Applications for S.B.A.C. Scholarships administered by the Society are invited from candidates between the ages of 16 and 18 years. The Scholarships are designed for the assistance of young men who are unable, for financial reasons, to take up a course of education fitting them to become aircraft engineers. Application forms may be obtained from the Secretary, to whom they should be returned by 30th June 1948.

OPEN SCHOLARSHIPS IN METALLURGY

The University of Birmingham will award six scholarships in 1948 of an annual value of £50, tenable for three years in the Department of Metallurgy.

The scholarships are eligible for supplementation by the Ministry of Education which is prepared to add a maintenance allowance, based on a means test.

Applicants must be of British nationality, born not earlier than 1st January 1923, and must have complied with the requirements of the Joint Matriculation Board for entry upon a degree course. They should possess the Higher School Certificate or be candidates for such certificates in the year in which they apply for the scholarship. Alternatively, they may possess the Intermediate B.Sc. of the University of London, or be candidates for the examination in the year of the award of the scholarship.

Candidates must present, or have presented, Chemistry, Physics and Mathematics at the Higher School Certificate Examination or London Intermediate Examination, two of the subjects being at principal or group standard.

Application forms may be obtained from the Registrar of the University of Birmingham, to whom completed forms must be returned by 30th June 1948.

ASSOCIATE FELLOWSHIP EXAMINATION

The next Associate Fellowship Examination under the present syllabus will be held on 1st, 2nd and 3rd June 1948. Those candidates who have registered with the Society will be informed individually of the detailed arrangements.

JOINT AERONAUTICAL CONFERENCE 1947

Publication of the complete proceedings of the Joint Aeronautical Conference, held from 3rd-5th September 1947, has been delayed slightly and is now expected to be ready early in May. The volume, of some 700-800 pages, will contain the twenty British and American papers together with the discussion on each, and a list of members.

Although the number to be printed is strictly limited a few more orders may still be accepted. The cost to members of the Conference is £2 12s. 6d. per volume and to non-members of the Conference £3 12s. 6d. per volume.

Remittances, payable to Aerial Science Ltd., should be sent with orders.

GRADUATES' AND STUDENTS' SECTION

Annual General Meeting

The Section's Annual General Meeting will be held on Wednesday, 21st April 1948, at 7 p.m., in the offices of the Society, 4 Hamilton Place, W.1.

AGENDA

1. To read the minutes of the previous Annual General Meeting.
2. To receive the Annual Report.
3. To elect officers and committee for 1948-49.
4. To consider any other business.

Nominations for officers and committee, signed by a proposer and seconder, and notice of business under item 4, should reach the Hon. Secretary, J. G. Roxburgh, 62 Fitzjohns Avenue, London, N.W.3, not later than three days before the meeting.

LECTURE PROGRAMME—1948

The Lectures will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, S.W.1 (by permission of the Council of the Institution) unless otherwise stated. Tea will be served at 5.30 p.m.

Visitors are welcome, but should obtain tickets through a member of the Society.

Thursday, 15th April 1948—Visual Aids for Low Visibility Conditions, by E. S. Calvert, B.Sc., A.R.C.Sc.I.

Thursday, 27th May 1948—The 36th Wilbur Wright Memorial Lecture. Size in Transport—A review of the development of the subject, with particular respect to size and the application of its lessons to Air Transport, by A. Gouge, B.Sc., F.R.Ae.S.

BRISTOL BRANCH

Wednesday, 14th April 1948—Film Night and Annual General Meeting. In the Conference Room, Bristol Aeroplane Co. Ltd., Filton House, at 6.0 p.m.

GLASGOW BRANCH

Saturday, 8th May 1948—Visit to Prestwick Airport. At 3 p.m.

Tuesday, 8th June 1948—Visit to The Glasgow Herald Office.

Saturday, 3rd July 1948—Visit to The Blackburn Aircraft Ltd., Clyde Factory, Dumbarton.

Thursday, 26th August 1948—" Lecturettes." At The Grand Hotel, Charing Cross, Glasgow.

Tuesday, 28th September 1948—A Film Evening, at 7.30 p.m., at Prestwick Airport.

Thursday, 28th October 1948—Lecture by a Branch Member, at 7.30 p.m., at The Grand Hotel, Charing Cross, Glasgow.

Tuesday, 30th November 1948—" Lecturettes," at 7.30 p.m., at Prestwick Airport.

Thursday, 23rd December 1948—ANNUAL GENERAL MEETING, at The Grand Hotel, Charing Cross, Glasgow.

Members are requested to notify the Secretary at least one week before any of the visits, if they intend to be present.

Visits are confined to members only, but visitors are welcomed at all Lectures, Lecturettes and Film Shows.

LUTON BRANCH

Wednesday, 5th May 1948—Large Flying Boats, by H. Knowler, F.R.Ae.S., at the George Hotel, Luton, at 7 p.m.

GRADUTES' AND STUDENTS' SECTION

Wednesday, 14th April 1948—The Influence of the Recent Civil Airworthiness Requirements on Civil Aircraft Design, by W. Tye, B.Sc., F.R.Ae.S., Air Registration Board.

Tuesday, 11th May 1948—The Light Aeroplane and the Future of Private Flying, by P. G. Masefield, M.A., F.R.Ae.S., Director General of Long Term Planning and Projects, Ministry of Civil Aviation.

All meetings will be held in the Library of the Royal Aeronautical Society, 1 Hamilton Place, W.1, at 7.30 p.m. *The Library will not be open before 7 p.m.*

FARNBOROUGH APPOINTMENT

The Civil Service Commissioners invite applications for the post of Principal Scientific Officer for Accidents Investigation in the Royal Aircraft Establishment, South Farnborough, Hants.

Candidates must be British subjects born on or before 1st August 1917. They must have a good honours degree in Engineering, Mathematics or a Science subject and possess ability in applying scientific method to a diversity of problems, particularly in the theory of structures, applied aerodynamics, aircraft design and applied statistics.

The successful candidate will be responsible, as Head of the Accidents Investigation Section, for co-ordinating the investigation of aircraft accidents referred to the Establishment for specialist opinion. Administrative assistance will be provided and encouragement given to undertake statistical or other original scientific work aimed at minimising the accident rate.

The appointment is permanent with superannuation benefits under the Federated Superannuation System for Universities. Inclusive salary scales are £860-£1,155 (men) and £760-£997 (women).

Further particulars and forms of application are obtainable from the Secretary, Civil Service Commission, Scientific Branch, 27 Grosvenor Square, London, W.1, quoting No. 2153, to whom completed application forms must be returned not later than 25*th May* 1948.

INCOME TAX

In response to numerous inquiries from members with regard to a rebate on Income Tax for their subscriptions, the following is a copy of a letter received from the Principal Inspector of Taxes.

Ref. H.R.S. 34/C.I. 4420/63.

Dear Sir,

Further to your interview with Mr. Stonely at this office on the 19th July, I am now in a position to inform you that the Board of Inland Revenue will not

raise objection to the allowance as an expense for Income Tax purposes of annual subscriptions paid by members who are:—

(i) Assessable under Schedule D of the Income Tax Acts in respect of professional or trading profits, subject to the decision of the Commissioners who make the assessment that such subscriptions are sufficiently closely related to the business on: or

(ii) Assessable under Schedule E in those cases only in which continual membership of the Society is an essential condition of the terms of appointment.

Yours faithfully,
(Signed) GEO. WILCOCK,
Principal Inspector of Taxes.

JOURNAL BINDING

Because of increased costs, the prices of binding of Journals will be as follows:—
1947 Volume 15/-.
Previous Volumes 17/-.

Journals should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the office of the Society.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

NEW MEMBERS

Associate Fellows

Eric Cutts Beard, George Stephenson Bowey, Alastair Hugh Cameron, R. Chambert-Loir, Ernest Charles Clear Hill (from Graduate), John Carol Collins (from Graduate), Roger Savernake Dickson, Ronald Dimerline (from Graduate), Jiri Dolezal (from Associate), Clement George Wilson Ebbutt (ex-Student), Maxwell John Edmonds (from Graduate), Arthur Evans, Ivor Everson (from Student), George William Futcher, Thomas Frederick Richard George, Sidney John Goates, William Kenneth Grant (from Associate), William Henry Gregory, Reginald Edward Wynyard Harland, Rex Anthony Harvey (from Graduate), Raymond Holl (from Graduate), Krishnagiri Thooppil Gopalakrishna Iyengar, David Mellor Jameson (from Graduate), James Morrison Johnston, John Kinsella, Arthur Turner Lancaster, Denys Marius Louw, Harold Lyne, Douglas MacKenzie, Owen Finlay MacLaren, Peter Fyfe Mouritz (from Graduate), Robert James Newton (from Graduate), Elton John Perks (from Graduate), Frank Pilkington (from Graduate), William Beesley Roy Pocock, R. Ravaud, John Philipp Milford Reid (from Graduate), Frederick Charles Sanders, Joseph Handford Stevens, Stuart Summersbee (from Graduate), Arthur Tannenbaum, Alfred Everett Thornton, Arthur Trevor Williams, William Trefor Williams.

Associates

Reginald Percy Bailey, Frederick John Ballard, Archibald Horace Cholerton, Thomas David, Myles Lonsdale Formby, John Reginald Gardiner (from Student), Ronald John Frederick Geary, Ronald Edward Green, Leslie Leetall Harland,

Alexander Saunders Johnston, Donald John Maxwell Keys, John Lawley Lendrem, Donald Lowry, Hubert Charles Beverley Mackey, Claude Percival May, Horatio Brian Hartley Parkhurst, William Hubert Perry, Thomas Picken, Harold Pound, William A. Rendell, Edward Charles Saggs, William Scott, Alexander Whitelaw Sinclair, John Daniel Snook (from Student), William Denis Learoyd Theed, Herbert Henry Watkinson, Wilfred George Wotton, Eric Paul Zander.

Graduates

Michael Thomas Caiger (from Student), Richard Henry Collins (from Student), Alan Charles Conolly, Thomas Frederick Curragh, Albert Denton Curry, Alan Donkin (from Student), Roy Farmer, Francis Leslie Freeman, Vernon Frederick Gardener (from Student), John Grieve (from Student), Stephen John Hancock, Edwin Jones, Mostyn David Kimber, Henry Anthony Knight (from Student), Dennis Lewis, Om Parkash Mediratta, Peter Meiklem (from Student), Catherine Gertrude Newton, Hedley James Organ, Raymond James Potter (from Student), Peter Robinson (from Student), Christopher Sutcliffe, John Thompson, John Bruce Thompson, Frank John Weight, Maurice Oliver Wilmer, Sydney Francis Wilson.

Students

Maurice Charles Baxter, Douglas Francis Beanland, Stephen Joseph Wyndham Brown, Donald Edward Brian de Casmaker, Ronald Cole, Eric Henry Crudden, Herbert David Denchfield, Henry Clare Eatock, Roland Anthony Gray, Aubrey Dillon Hill, Edward Louis Houghton, Norman Jackson, Simon Kugler, Anthony Charles Edward Leach, Alexander Vivian Leake, Victor Taylor Legge, John Dennis Micklem, Brian Ronald Morris, Thomas William Neil, Godfrey Edward Noble, Rosslyn Phillips, John Pringle, Richard George Proudlove, Geoffrey Reece Scott, Sidney Charles Swatton.

Companions

John Stuart Rowland Muller-Rowland, Ronald Selby Walker.

J. LAURENCE PRITCHARD,
Secretary.

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The Royal Aeronautical Society

ACTIVITIES OF THE GRADUATES' AND STUDENTS' SECTION

April 1948

On Tuesday 11th May the Section will hold its last lecture of the session when Mr. P. G. Masefield, M.A., F.R.Ae.S., Director-General of Long-Term Planning and Projects, Ministry of Civil Aviation, will speak on "The Light Aeroplane and the Future of Private Flying."

Members are further reminded that the Section's annual general meeting takes place on Wednesday 21st April, and it is hoped that this meeting will be well attended so that the Section's future activities may be fully discussed.

LECTURE

The following is a summary of a lecture entitled "Suction Aerofoils and the Principles of Boundary Layer Control" by Mr. B. Thwaites of Imperial College, London, which was held in the Library of the Society on Wednesday 25th February 1948. Mr. J. W. F. Housego was in the chair.

Mr. Thwaites began with a short historical survey, from 1904 when Prandtl first introduced the so-called boundary-layer equation of motion, to 1940 when Griffith proposed applying suction at a discontinuity in a specially designed aerofoil; and to 1945 when Preston showed some of the possibilities of porous suction.

Boundary layer suction through a slot can be put to the following purposes:—

1. *To extend a region of laminar flow.* If a slot is placed just before the point of transition to turbulence, a much thinner boundary layer will start behind the slot and will remain laminar for a greater distance than would the original layer. In this case the amount of suction depends on the distance transition is to be delayed, but clearly transition cannot be postponed indefinitely by one such slot.

2. *To convert a turbulent boundary-layer to a laminar one.* Here the whole (and possibly a bit more) of a turbulent layer is sucked away and a new laminar layer is started behind the slot.

3. *Delay of separation.* If a boundary layer which is just about to separate from the surface is sucked away, a new one is started, which if it separates, will do so farther down stream.

4. *Prevention of separation.* There is a certain point at which if separation there is suppressed, then it will not recur elsewhere. This is the essence of the Griffith scheme, the point chosen for suction being the discontinuity in pressure at which separation would normally take place. The amount of suction depends on many things, the total surface pressure rise, whether or not the boundary layer is laminar or turbulent, and so on.

Continuous suction through a porous surface presents a method of maintaining a thin boundary layer, with, moreover, a very stable profile, so that disturbances are more likely to be damped out. Considerable economies in the quantity of air to be sucked away to prevent separation can be achieved by this method, although other difficulties of an obvious character must be overcome.

Blowing in a down-stream direction through a slot has been used to increase the energy of a boundary layer so that it can overcome a greater pressure rise without separation.

Having laid out the different functions of boundary-layer slots and continuous suction, Mr. Thwaites gave a brief account of their application to aerofoils.

First, the prevention of separation at the rear of a thick aerofoil by suction through a number of slots. It is doubtful if this system would be used in practice, since the quantities to be handled are very large.

Next, the substitution of a laminar layer for a turbulent one. The main application is to the front part of a wing where transition may be caused by flies, grit or rivet heads. If a slot is located behind the main area of irritation and the aerofoil is designed to have a falling pressure for some distance rearward, laminar flow can be achieved behind the slot.

Suction slots spaced round the entire surface can be used to maintain laminar flow over a normal profile, and experiments of this nature have been made in Zurich. However, the quantities are large, and the practical difficulties of such an arrangement are obvious.

The next important case is the Griffith type aerofoil, where suction is applied at a local discontinuity in pressure, thereby preventing separation. This technique is best applied to thick aerofoils. The contour is designed, either by the exact or the approximate mathematical methods available, so that the velocity increases up to the slot. Thus there is no possibility of separation and every chance of laminar flow up to this point. After the discontinuity there is no chance of laminar flow, since the boundary layer on the concave surface is dynamically unstable, but the rising velocity continues to prevent separation. Because of the thickness, enormous C_L ranges can be designed for, of ± 1.0 or, on a cambered aerofoil, of 0 to 2.0.

Allowing for ideal pump work in the form of a drag coefficient, the total drag of a 30 per cent. thick aerofoil may be reduced to less than that of an ordinary thin low-drag aerofoil by the use of this form of suction.

Suction at a slot can be used to delay separation on high lift thin aerofoils. The normal steep adverse gradient near the nose is replaced by an even steeper, localised gradient, followed by a more moderate slope. Suction is applied in the vicinity of the steep gradient, with the result that separation of flow is delayed and an increase of lift obtained.

It has been shown that with continuous suction of sufficient intensity it is possible to maintain laminar flow in the presence of unfavourable gradients. Thus we have a possible solution to the problem of premature transition due to dust, grit, flies or waviness.

Porous suction can also be used to prevent separation at the rear of thick aerofoils. Convincing demonstration of this possibility has been made by the complete suppression of separation on a circular cylinder in the wind tunnel.

Mr. Thwaites ended his lecture with a short survey of further developments and then dealt with a number of questions from the audience.

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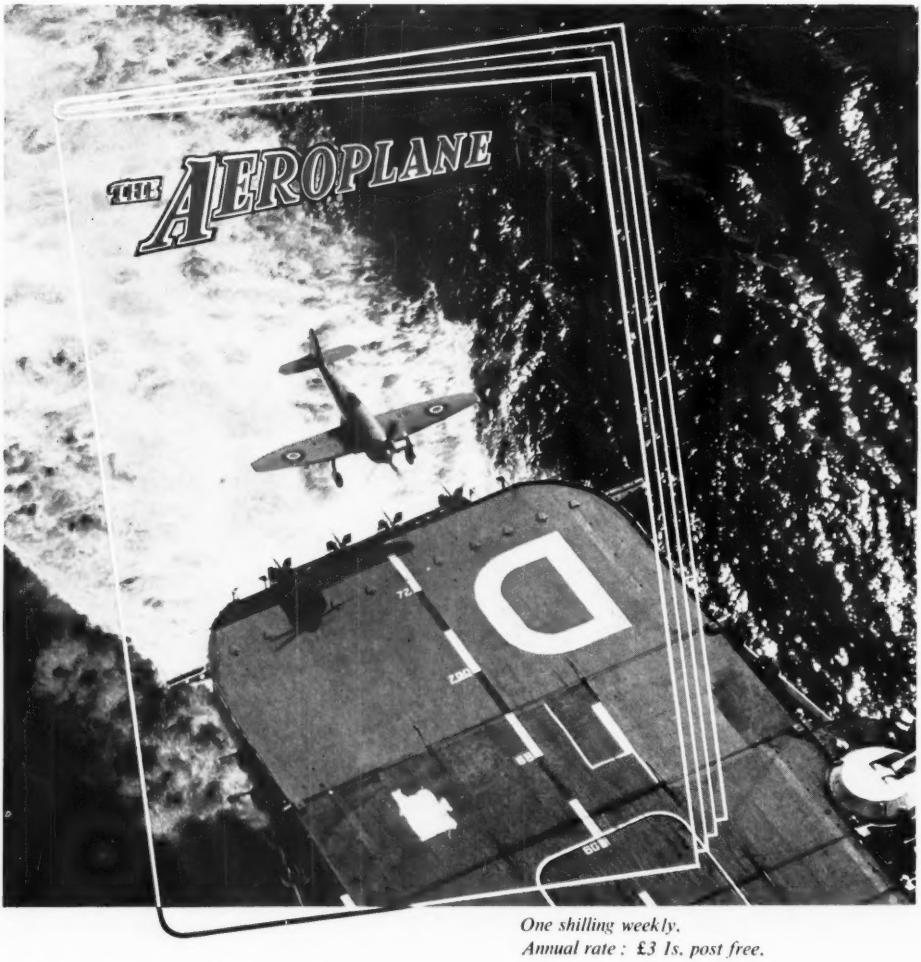

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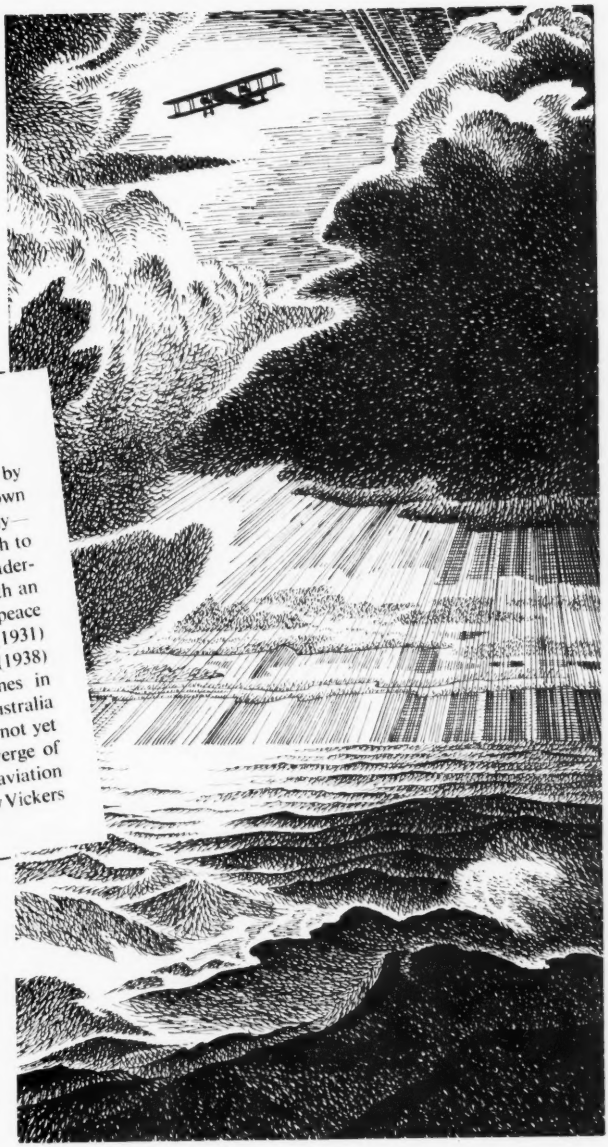

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A.T.24

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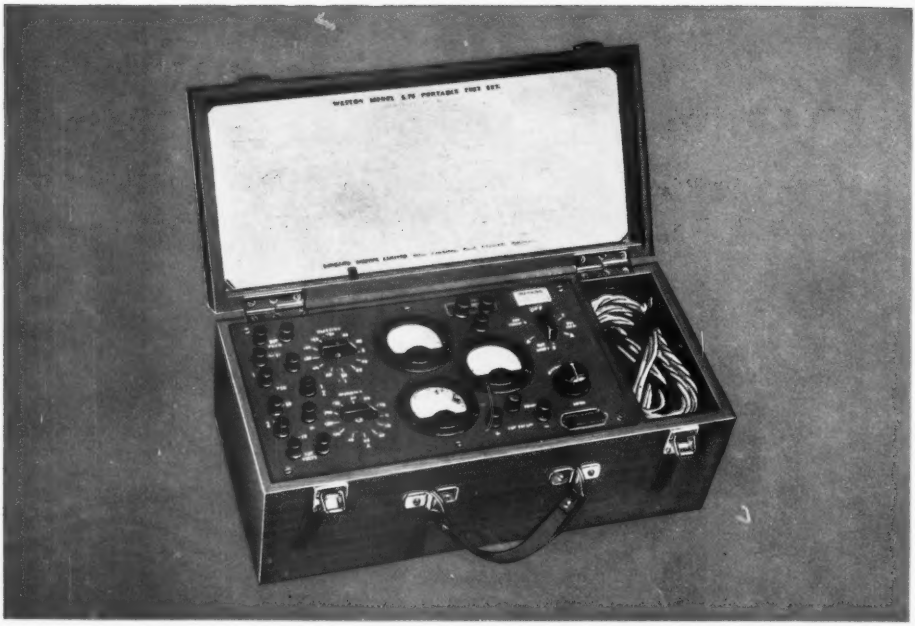

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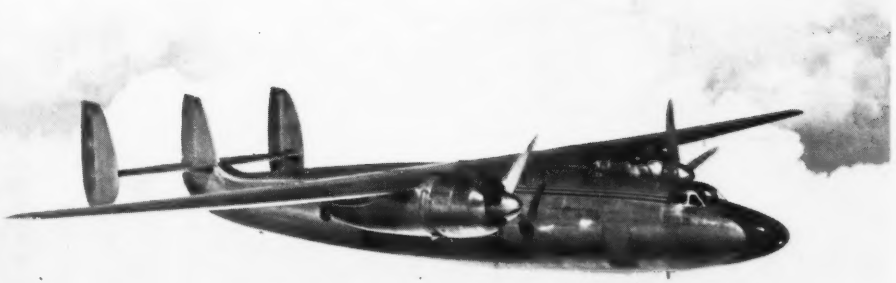

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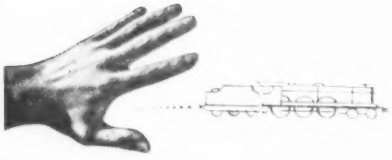

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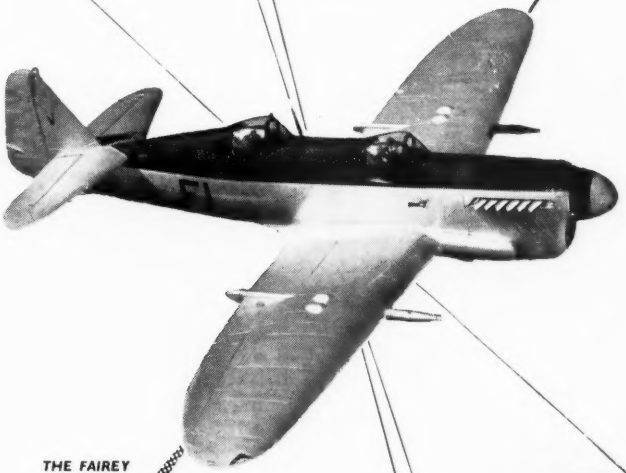

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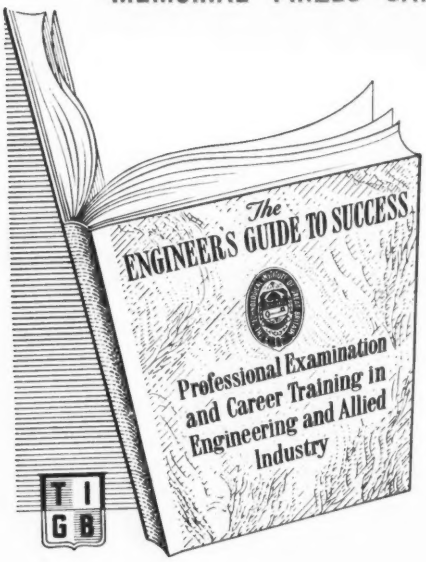
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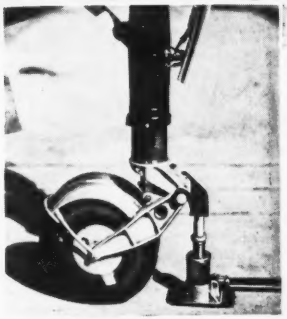

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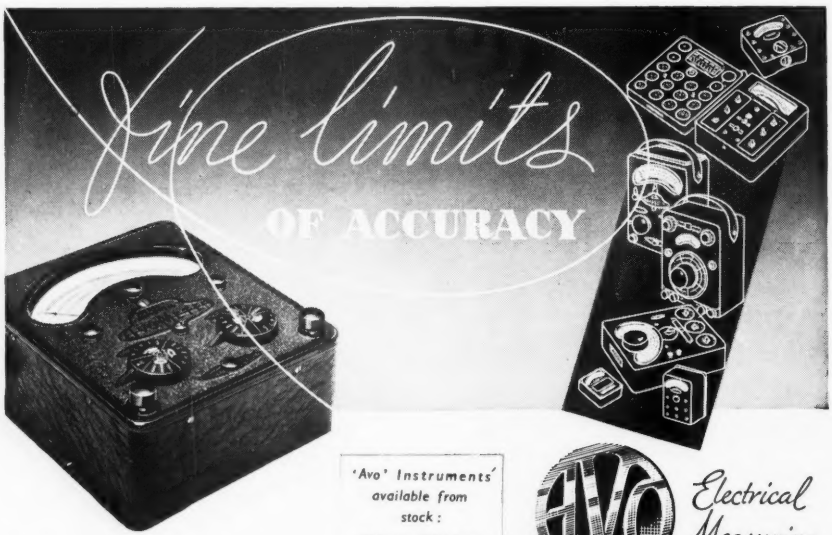

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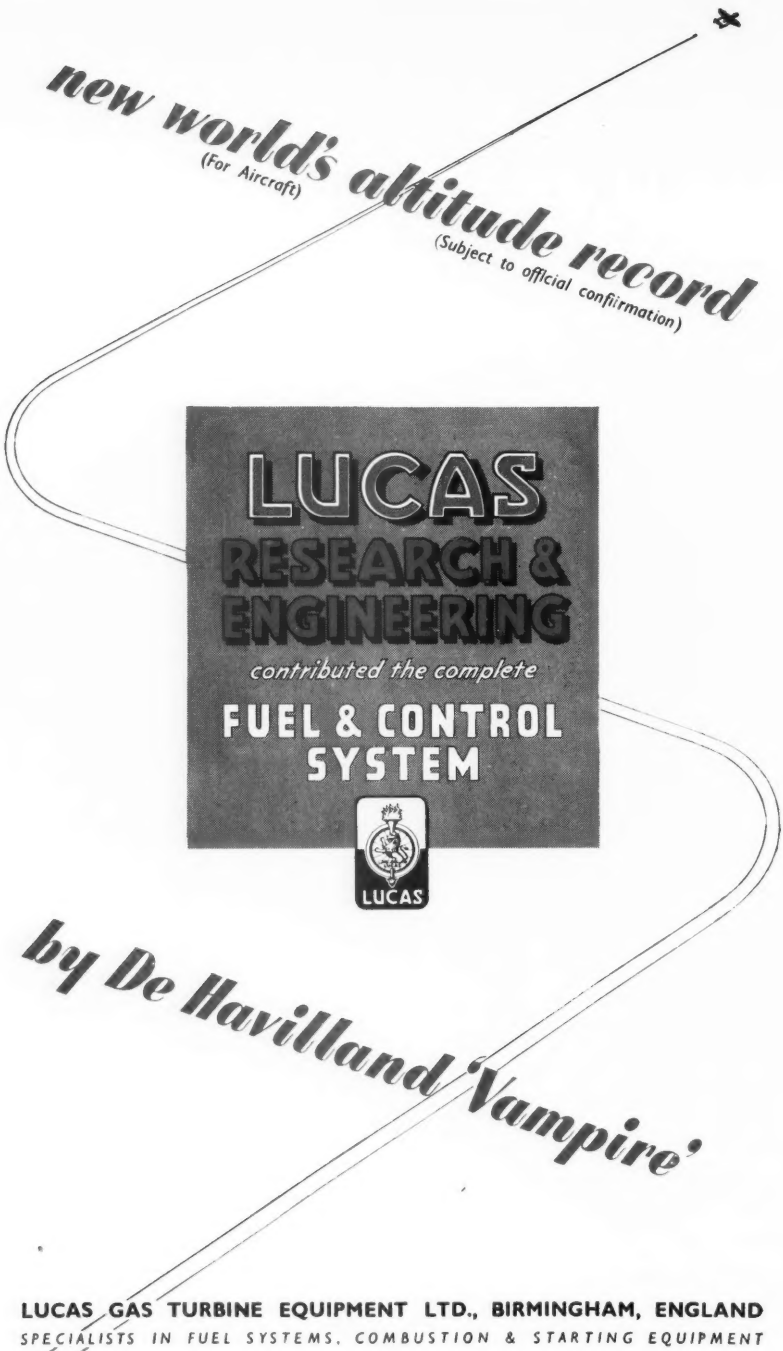

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AIRCRAFT AND THE AIRLINES – A CANADIAN VIEW

by

JAMES T. BAIN

Mr. Bain entered the R.A.F. at Cranwell in 1921 *and served for ten years on the engineering side. On leaving the R.A.F. he joined Hillman Airways and then served with Scottish Motor Traction (whose services were taken over by Railway Air Services), Spartan Airlines and the original British Airways Ltd. He served with British Airways Ltd. in an engineering and maintenance capacity, being responsible among other things for starting up the maintenance side of Gatwick Airport. In* 1938 *he went to Canada to join Trans-Canada Air Lines and is now Director of Engineering and Maintenance with the Company. He has done much of the work on the Canadian-built DC-4M (Rolls-Royce engines) series, being responsible for the specification for this aircraft, and was on loan to Canadair Ltd. for* 15 *months to supervise the building of this type.*

THE THIRD British Commonwealth and Empire Lecture was delivered before the Society by Mr. James T. Bain on Thursday, 30th October 1947 at the Institution of Civil Engineers, Great George Street, London, S.W.1. The chair was taken by Dr. H. Roxbee Cox, F.R.Ae.S., President of the Society.

The President: There were two major lectures given during each session before The Royal Aeronautical Society. One was the Wilbur Wright Lecture, founded in 1913, and the other the British Commonwealth and Empire Lecture which was founded more recently. The Third Lecture of the latter series was to be given that evening.

In founding the Lectures, the Council wished to encourage fresh ideas and new viewpoints from all parts of the British Commonwealth and Empire, and because of the status which they attached to it, it was a considerable distinction to be asked to give a lecture.

The first lecture of the series, in 1945, came from Australia and was given by Mr. W. Hudson Fysh of Qantas Empire Airways; the second was from England, given by Sir Henry Self, at that time Permanent Secretary of the Ministry of Civil Aviation; and the third was to be given by Mr. James Bain of Trans-Canada Air Lines.

Mr. Bain had come from Canada purposely to deliver the lecture and consequently, he was very pleased to see such a distinguished audience. At the same time, although Mr. Bain had come from Canada, to say whether or not he could properly be described as a Canadian was less certain, as he had entered the R.A.F. at Cranwell in 1921 and served for ten years. He had then spent seven years with British air line companies. He had worked always on the engineering and maintenance side of aviation and had gained a great deal of experience before he went to Canada in 1938 to join Trans-Canada Air Lines. Now he was Director of Engineering and Maintenance of that Company.

The Society, therefore, had as the third British Commonwealth and Empire Lecturer one who had spent all his working life on the engineering side of aviation and the past seventeen years as an engineer in connection with air transport; in other words, a man who spoke with authority.

Mr. Bain presented his paper.

The privilege and honour extended by the Royal Aeronautical Society in inviting me to deliver this paper are very deeply appreciated.

INTRODUCTION.

In common with all airline men, there is not the slightest doubt in my mind that aviation will develop into the major method of transport. Everything is in its favour. Already it is the fastest known mode of conveyance; ultimately it will be the most comfortable and finally, it will be the least expensive. All that is required is common sense, hard work and adherence to the high ideals which have guided the enthusiastic men whose faith has propelled us thus far along the road.

I am going to be somewhat severe in criticism of the airlines and of the industry in general but, at the same time, I shall try to give you some of the requirements of airline operation and some possible corrections to the present deficiencies.

By way of introducing the subject matter of my paper, I should like to take a few minutes to sketch for you, as I see it, the picture of the North American airlines. Throughout the discussions which follow, I shall use the North American airlines as the examples. This is done for two reasons. First, it is with the airlines of Canada and the United States that I am most familiar and second, because of the relatively greater spaces and the distribution of centres of industry and population, airline travel has been intensified in North America to a greater degree than anywhere else in the world.

The picture I shall present is by no means a happy one, and one which I believe will eventually apply to any one of the world's major airlines. It is my belief that from that picture there are lessons to be learned; lessons of great value to those countries which have yet intensively to develop their airlines.

PRESENT STATUS OF NORTH AMERICAN AIRLINES.

Since the end of World War II the airlines have done more business, yet made less money, than ever before in their histories. Passenger revenues have gone up by leaps and bounds, but the gain has been completely offset by the even more spectacular leaps and bounds of operating expenses. There are many empty seats on the airlines these days and at the same time, air mail and air cargo revenues have fallen off badly in their proportion of the total. The overall situation in the aircraft industry is poor and gives cause for serious alarm. When the hard facts of pounds, shillings and pence are studied, it is obvious that the financial security which is prerequisite to successful operation is definitely lacking. At the present time there is plenty of evidence of narrowly averted economic disaster, disaster which is still being staved off by re-financing, mergers, increases in rate structures or straight increases in subsidies.

The last few months of the winter 1946-47 was a period of grave suspense. Always a highly seasonal business—that is one of the main deficiencies of the airlines—no one knew how far the midwinter slump would recover with the return of better flying weather or what would be the permanent effect of the series of major aircraft accidents which occurred all over the world. There has been a considerable recovery but as yet it has been insufficient to give a comfortable margin in black figures.

The reasons for this dilemma of poverty in the face of increased revenues are many and varied, but outstanding among these reasons is the fact that present airline aircraft, and the facilities they use, are basically unsuited for any greatly expanded or accelerated operations.

My paper is an attempt to point out some of the present deficiencies, as I see them, of aircraft and aircraft operations. I shall say things that will not be accepted or will be lightly dismissed or torn to bits to the satisfaction of the individual critic. Whether or not the suggested remedies for the problems are correct, the problems themselves are incontrovertible facts; facts which too long have been pushed into the background and which must be faced.

PRESENT AIRLINE AIRCRAFT.

First let us examine our present airline aircraft and see what they are and from where they came.

During the recent war the world's airlines did a magnificent job in the face of many difficulties. Considering the shortages of aircraft, equipment, ground facilities and personnel, the standards and volume of air-

line operations were excellent. Schedules were increased to the maximum, with perhaps some sacrifices of passenger convenience and comfort, but the record proves there was no relaxation of maintenance and flight operators' standards. This great job was done with the self-same aircraft which had already served some years as standard airline equipment; aircraft already old in design which in 1939 were about to be replaced by more up-to-date and larger types.

The war years also saw the formation and mushroom growth of the great Allied Air Transport Commands; organisations which in large part were built up and operated by airline men seconded to military service for the duration of the war. The equipment used by the Transport Commands was comprised of commandeered airline equipment, converted military types and the airline aircraft which were in the final design stages in 1939. These airline types were rushed to completion in military garb and ultimately became the backbone of all Transport Command services.

THE POST-WAR "INTERIM" AIRCRAFT.

Throughout the war the airlines were desperately short of aircraft, so it is understandable that, with the close of the war in Europe, an immediate clamour arose for more aircraft for the airlines. With the release for sale or rent of some of the older Transport Command aircraft, there was a rush to reconvert these types and get them into service. Airline fleets were amplified quickly and there followed a tremendous expansion of airline routes and frequencies, as well as a mushroom growth of non-scheduled operators who were trying to get into the "big money."

Some idea of the expansion of the airlines (excluding the non-scheduled operators) can be obtained by comparing the published figures of the United States operators. In 1946 the total revenue passenger miles flown was two hundred and seventy per cent. of the totals for 1944. In 1947 a conservative estimate places the expansion at four hundred and fifty per cent. of the same datum.

Remarkable as these figures are, they still do not tell the whole story. The estimated four hundred and fifty per cent. represents passengers who will actually be carried, but in 1944 the payloads were about the maximum which can be achieved in operation; almost universally they were in the region of ninety per cent. To-day the average payload factors are closer to sixty per cent. From this we can deduce that the passenger miles available in 1947 show an increase of six hundred and ten per cent. over 1944.

This figure gives some indication of the increase of capital equipment on the airlines.

These tremendously expanded airline fleets were comprised entirely of makeshift conversions of military aircraft, or venerable airline aircraft for which the basic designs were laid down between eight and thirteen years ago. They are the same aircraft on which the pre-war airline industry was built, or are the aircraft which were in process of manufacture to meet 1939 airline requirements.

THE "NEW" AIRCRAFT.

Let us go one step farther and examine the origin of the so-called new aircraft which are now finding their way into service on the airways.

In the latter months of the war the over-zealous publicity men in and out of the aircraft industry promised the world great new fleets of wondrous luxury aircraft, which were apparently going to materialise overnight. They did a good job of it—these publicity men; so good a job in fact that they succeeded completely in making even the leaders of the aircraft industry believe in their rosy predictions. These dreams of 1944 and 1945 have now completely vanished and reality shows us the anticlimax of rehashed versions of pre-war designs, or new models built along the same old design principles.

Two major factors have contributed to bring this about. First, the stampede of the airlines to buy additional equipment forced the manufacturers to promise to produce new aircraft quickly. This they were glad to do in order to retain enough business to keep their doors open. Second, the manufacturers, faced as they were with the airlines' demands for the speedy production of new aircraft, did the best they could to take full advantage of the wartime tools and designs already in their plants. They did not take time to restudy the new airline pattern that had leaped into being after the war. They did not study the operational result which would

attend the expanded fleets of larger aircraft when placed in operation on the existing airway facilities; airway facilities which, with but minor embellishments, are the same to-day as they were before the war.

I wish to repeat my statement on the "new" aircraft. They are, by and large, rehashed pre-war designs, conversions of military aircraft, or are new versions built to meet the same old design principles. They are new only in terms of production date.

These aircraft now on order, or going into service on the airlines, have been purchased with the pious hope that the product of increased speed and capacity will give the revenues with which to meet the inflated costs of operation. I hope this proves to be correct, but, when one considers the new regulations under which these new aeroplanes will operate and such necessary impending international agreement as "temperature accountability," it is hard to believe that the latest additions to the airline fleets will meet their purchasers' requirements.

My own opinion is that the new aircraft are little, if any, better than the old, and the necessary improvement in the operating results will not materialise.

Such then, as I see it, is the present picture of the airlines and the flight equipment being used in the endeavour to expand and accelerate operations. From the record of recent operations it is clear that around some major cities the expansion of airline routes and frequencies has already exceeded the ultimate for the facilities and equipment available.

Before proceeding farther there is one point which must be made clear. As a vehicle, the present airline aeroplane is sound and is capable of reasonable success when carefully operated within its limitations. If an airline is prepared to continue operation with strictly limited density of traffic, to spend a lot of money counteracting the irritations of poor regularity, and can still make enough money to stay in business, then the present airline aircraft are perfectly satisfactory for their purpose.

Handled properly on routes which provide the necessary latitude, these tried and proven aircraft of vintage design will do a fair and reliable job; but, improperly handled in an attempt to carry greatly expanded and accelerated traffic volumes, these same aircraft and the facilities they use are basically inadequate for the purpose.

Having shown to at least my own satisfaction, the limitations of what we presently have, let us see what improvements can be made by examining the deficiencies and establishing what changes are necessary in aircraft specifications.

One basic factor must always be kept in mind. Aircraft specifications must be developed to meet the particular requirements of the route, the traffic and the type of operation. Up to the present the narrow margin beween operating profit and loss makes it essential that the tools (aeroplanes) with which we work be designed for maximum efficiency. There is no such thing as a general specification.

Examination of specification breaks down readily into two main sections. First, the aircraft in the air and, second, the aircraft on the ground.

THE AIRCRAFT IN THE AIR.

Regularity in flight operations.

The greatest of all evils in airline travel is undoubtedly the lack of ability to maintain schedule. Against this major defect all others become minor in importance and relatively easy to improve. There are few functions in airline operation which do not in some degree affect regularity and it certainly is true that every factor which affects regularity of operation is closely related to the development of satisfactory specifications for airline aircraft.

To make a complete study of regularity and the effect on specification, it would be necessary to start with a thorough examination of how to sell tickets to the customers. Such a study is beyond the scope of this paper and it is necessary to confine discussion to a few of the major factors involved.

(1) *Safety in flight operation.*

As a factor in achievement of regularity, safety in flight operations undoubtedly must be the first one considered.

The winter of 1946-47 saw a series of major airline accidents which gave both the travelling public and the airlines much to consider. These tragedies touched off a veritable spate of commentary and publicity which, in the minds of thousands of potential air travellers, left the indelible impression that "flying is not safe." For years to come the damage has been done. To digress a

little for a moment, there is one factor which has contributed largely to the reaction of the man in the street.

Each accident is wrapped up in a shroud of secrecy which is not removed until the incident has faded completely from the public mind. If free and open discussion of the cause of the accident and the correction which had been applied were released while the incident was still fresh, the airlines would have gone a long way towards giving their customers the necessary reassurance that, when properly operated, the aeroplane is as safe as any other transport vehicle.

The only counteracting measure by which the airlines have attempted to confound the critics, is the publishing of defensive statistics which prove that the accident rate in scheduled operation has steadily decreased over the past decade. What value these statistics have, I do not know. To point out that an airline passenger is a much better insurance risk than a passenger in a private motor car is of little value in the face of the fact that the accidents occurred. That fact says quite clearly that we are not yet good enough.

As a result of last winter's airline accidents, powerful investigation committees were set up at high government levels. These have been successful in effecting a little house-cleaning and there is no doubt that such investigations will result in a further decrease in accident rate, and probably some of the causes of air accidents will be eliminated completely. Whether or not the corrections being made will meet the case will be proved only by the future record, but my own opinion is that, if the committees continue their investigations along the same lines as at present, then their digging will not get down to the real roots of air accidents.

There can be no true regularity unless it is regularity with safety. It is failure to recognise this basic truth which keeps regularity indifferent and the accident rate too high. I shall have to go back in airline history to make my point.

In the early days of scheduled flying the aeroplane was by no means the complicated mechanism we know to-day. Everything about it was rudimentary, and flying was stopped when it was not possible to see the ground and follow the course of the flight on a map.

The succeeding years saw the rapid development of the first airline aeroplanes. Great strides were made in the reliability of engines and airframes which increased the scope and reliability of operations, and the development of radio and precision instruments made it possible to navigate without visual contact with the ground. With each advance of specialised equipment, the regularity and the safety of scheduled operations were improved. New problems such as icing, static and storm were studied, understood and beaten by additional equipment or advance of the associated sciences. Scheduled flying became possible through all but the worst weather conditions. This was roughly the status in 1940. But somewhere along that road of progress an essential turning has been missed. We are not progressing any more.

Some months ago I was talking to an old and thoroughly experienced airline captain. During our conversation on this subject of safety and regularity he made what is, I believe, a very significant remark. He said: "With anything approaching minimum weather conditions, flying into LaGuardia these days is a full-time job for two men working independently."

What he said in effect was that the airline procedures which have been developed to give regularity of operation have gone beyond the point where regularity and safety went forward together or, to put it another way, we now are striving for regularity at the expense of safety.

When first a sensitive altimeter was installed in an aeroplane the pilot of the aircraft was given an instrument which permitted him to operate with safety into lower minimums of cloud height than ever before. Thus, in this elementary case, were regularity and safety both improved, but in the course of developing the airline aeroplane there have been added new techniques, procedures and additional gadgets beyond the ability of any human being to act as the interpreting or controlling medium.

A glance at the record of accidents proves beyond doubt that the human element is the major weakness in the safety of aircraft operations. With this positive knowledge it must be quite obvious that any further addition of procedure or gadget or supernumerary crew can only result in a further over-loading of the already over-burdened human element.

Look at the same question from another viewpoint. With the expansion and acceleration of airline traffic which has already taken place at some of the major cities in the U.S.A., each minor weather delay causes the "stacking" of flights above the airport sometimes for hours, awaiting their turn to land. A major deterioration in weather will ground flights for a considerable radius for periods of time which force cancellations of schedule, with all the attendant expense, complication and loss of goodwill.

Regularity has already deteriorated in the congested areas. What, therefore, will be the effect of the still greater increases in traffic density which have been so prolifically forecast?

For these increased traffic densities it has long been my opinion that full and complete automatic control is the only possible answer. There can be no compromise; the human element with its limited and slow powers of co-ordination must be eliminated entirely. We must do the same thing with aircraft operation as has been done with precision for many years by the underground rail system in London.

At no time during a flight's progress should it be necessary for the human element to take a part in the purely mechanical job of flying an aeroplane. There must be provision for:—

1. Automatic control of the flight from take-off to the end of the landing run at a destination.
2. Automatic two-way reporting and recording of aircraft position and progress.
3. Complete automatic air terminal traffic control from point of entry into the terminal area.
4. Control of the aircraft at all times providing automatic protection against collision and flight in excessively turbulent air.
5. Automatic power plant control including automatic "fail safe" provision against mechanical trouble or power failure. Control of power must be co-ordinated with air speed demands.

With these major features provided, the duties of the flight crews will be the monitoring of the automatic controls and governing the conditions of the flight. Captains of aeroplanes will become captains in the true sense of the word.

Complete automatic control is not impossible. Wartime expenditures have already provided the basic information from which can be obtained the answers to the remaining problems. This fact has already been amply demonstrated by the remarkable record of the "All Weather Airline" group of the United States Army Air Forces. If the airlines and their respective governments would adopt the principle of automatic flight control, aggressively pursue with complete achievement their goal, then the improvement in both regularity and safety would repay their investment many times over by increased operating revenues.

The airlines of the world and their respective governments have a gigantic responsibility. Up to the present time they have failed miserably to lay the basis of sound international air commerce. Since the end of the war there has been an effort to obtain international agreement on standardised operating procedures and equipment. Success has attended the efforts of P.I.C.A.O. (now I.C.A.O.) and I.A.T.A. to the extent that we do have agreement on tariffs and monetary arrangements. Some progress has been made towards an internationally agreed standard of airworthiness, but there is a long way to go still. As a result of months of conference, international agreement was reached (on paper) on operating facilities and procedures but as yet, there have been few or no practical results. For one reason or another these paper agreements have not been implemented.

Let me give an example. At the time of the Chicago conference of P.I.C.A.O., a communications committee was appointed to establish the standards of the radio facilities necessary for international navigation and communications. For many months the best brains in the industry struggled with this complex and difficult problem and, finally, a major degree of agreement was reached for certain zones of operation. Specific agreement was reached on the radio facilities for the North Atlantic yet, two years later, there exists a state of chaos which is a major penalty on all operations between Europe and North America.

Had the international standard agreed at Dublin in 1946 been implemented, a maximum of six frequencies would have been necessary between Montreal and London. At the present moment every aeroplane is

hauling the deadweight of equipment that provides the twenty-nine frequencies that are encountered over the same route. In addition to the obvious operational penalty, the failure to implement the agreed standards has given the flight crews more to handle and introduced greater possibilities of equipment breakdown or "human element" errors.

The aeroplane will never be a simple mechanism but it can be made simple to operate. In the interests of safety in the air this must be achieved. A great step forward will be taken when the airlines and their governments put into practice the agreements which have already been made.

(2) *Speed of flight.*

As a second factor affecting regularity of operation, speed of flight is of major importance. There is no travel distance over which the speed of the aeroplane is not superior to that of any existing form of ground transport. Speed of transport and speed alone is responsible for the creation, the existence and the tolerance of the airlines. Speed is the airlines' stock in trade. Without it they have nothing. With other things remaining equal, the more the speed of airline travel the greater will be the reward.

In a recent trade paper I read an editorial with the title of "Speed Obsession." It was representative of much of the nonsense that has been written by the "speed is already great enough" school of thought. The usual line of attack by these slow, easy and comfortable people runs something like this: Speed is dangerous, speed is expensive, speed adds a lot of complicated gadgets and accessories, or, from the passenger's point of view, there is not much gain in increased speed unless something is done about the all-inclusive journey time. With these pessimists I entirely disagree.

Over areas adequately served by surface transport, the speed advantage of the aeroplane decreases with the journey length. For example, while three and a half days can be taken off the train jounrney time from Montreal to Vancouver (2,579 miles), there is little, if any, time advantage in flying from Montreal to Ottawa (92 miles). In spite of this, no minimum airline journey length can be arbitrarily set as this is governed entirely by the local stage-to-stage conditions.

Trans-Canada Air Lines domestic routes total 8,183 miles, but the length of passenger journey averages only 536 miles. For every passenger who flies from Montreal to Vancouver there are fourteen who fly between Montreal and Toronto. It can readily be shown from statistics that the greatest demands for transport are over the short distances between adjacent populated areas, and it is for these short distances that the present airline is of least value.

It has been argued that increased speed over these short distances is of little benefit to the airline passenger in the total elapsed time from his own office desk to a downtown office at his destination. This is admittedly true, but it must be remembered, when examining all-inclusive journeys of this nature, that one is making a study of minimum journey lengths and not of the speed of flight. Aircraft speed is only one factor among many in such studies.

Earlier I said the airline business was a hard one of pounds, shillings and pence, so let us forget the passenger for a few minutes and examine some of the advantages which will accrue to the airline operator from increased speed.

1. The faster an aircraft can fly, the more units of work it can produce for every hour in the air.
2. By increasing the units of work produced per hour flown, fewer aircraft will be required. Thus, an increase in speed will save on initial capital expenditures.
3. With each improvement in speed, so will the speed of disposition be proportionally improved. With better speed of disposition, fewer spare or stand-by aircraft will be required, thus again saving on initial capital expenditures.
4. The faster an aircraft can travel from point to point, so will the inaccuracies of weather forecasting be reduced. If the speed of the aircraft is doubled, then the possibility of weather delay because of inaccurate forecasting is appreciably reduced. Thus can be obtained an immediate and substantial improvement in regularity. Greater regularity, in turn, will induce more traffic and permit a higher percentage of direct flights. This could only result in increased revenue and decreased operating costs.
5. The shorter the time taken to complete a journey, the less will be the many

incidental costs of meal services, hotel accommodations for delayed passengers, crew layovers away from base, and so on.

6. The combination of increased speed of disposition, greater regularity and the potentially greater traffic volume will bring the airlines closer to the possibility of eliminating the necessity of reservations for single-stage journeys.

In spite of these considerations the sceptics will probably remain unconvinced and mumble about high initial costs, high fuel costs and high operation costs, so I shall labour the point a little more and introduce another factor which is very important.

Without attempting to get into summer and winter seasonal traffic flows and the many other elements which affect airline operating costs, I should like to demonstrate the effect of speed increase on the costs of operation. I shall ask you to accept a rough formula for direct operating costs as being those which are directly proportional to the number of hours flown (such as fuel, oil, flight crew, overhaul, and so on) and for indirect costs as being those which remain constant regardless of the number of hours flown (such as depreciation of aircraft and ground equipment, hangars, traffic department, and so on). With existing airline aircraft the direct and indirect operating costs are each roughly 50 per cent. of the total operating costs when the utilisation of the aircraft is about 10 hours per day.

If the rate of producing work of the aircraft is doubled by the process of doubling the speed, then the original amount of work can be produced by half the number of aircraft. By halving the number of aircraft the major portion of the indirect costs is also halved. This means that the same amount of revenue can be produced at a lower total operating cost.

The old formulæ used to evaluate the operating costs and procedures of airline aircraft are overdue for drastic overhauling. The development of the turbine engine has introduced a new set of fundamental considerations. The commercial adoption of the turbine engine opens up vistas of substantial speed increase, together with appreciable reduction of operating costs.

Later on there will be further reference to the economics of fast aircraft but, for the present, I will finish this discussion of speed of flight by recalling to the memory of some of those present an old piece of airline history. Back in the middle thirties Imperial Airways Limited were giving first-class service and excellent meals on board the large, slow HP-42's on the run between Croydon and Le Bourget. They had no competition other than from aircraft of similar general performance until the original British Airways Limited put some Lockheed 10A's on the same route. These excellent little aircraft had nothing to offer the passenger except a substantial increase in speed, and they almost put the big aircraft out of service by taking away all the customers.

THE AIRCRAFT ON THE GROUND.

THE AIR TRAVELLER'S POINT OF VIEW.

As an airline man I recently squirmed when confronted with an advertisement published by a North American Railway Company. It read, "Relax! Next time take the train."

The majority of air travellers are provided with the fast transport they pay for, but it is, unfortunately, true that for many a passenger air travel has lost its erstwhile glamour of blue skies, silver wings and flashing speed. The air traveller of to-day is becoming more and more impatient with the multitude of irritations and delays which may beset his journey. The complicated reservations systems, the annoyance of picking up the ticket far ahead of departure time, the fuss over baggage and checking in, the overcrowding of the wild bus or taxi ride to the airport, the waiting for the departure, the service delays, connection delays, loading delays, weather delays, and mechanical delays, the supreme affront of cancelled flights, or the final bogging down at some alternate airport miles from the proper destination, all add up to account for quite a percentage of the empty seats on the airlines. When these basic evils are accompanied by the minor annoyances of inadequate and crowded terminal buildings, no place to sit or eat in comfort, poor ventilation, poor lighting, the incessant unintelligible blare of loudspeakers, the perishing cold or the blistering heat, or the mad dash through the rain to the waiting aircraft which seems to park invariably in the middle of a huge puddle, it is no wonder the poor air traveller is given seriously to think when his magazine or billboard says, "Relax! Next time take

the train." One could become very despondent about the future of the airlines if it were not for the statistical facts of the yearly increases in air traffic, which prove what can be expected when the bad conditions are corrected.

The lesser irritations will vanish quickly when improved airline financial results make the necessary funds available. The more troublesome of these deficiencies can only be eliminated by the building of airline aircraft designed to suit the operating conditions.

Let us examine some of the factors which directly affect the development of a satisfactory specification.

STATION HANDLING OF EN ROUTE AIRCRAFT.

It has long been a desire of mine to have one of the designers of airline aircraft spend just one week on the departure ramp at an airline station. At the end of that short period he would thoroughly appreciate that it takes more than a knowledge of aerodynamics to design a good airline aircraft.

He would soon understand why lack of the proper facilities of the aircraft for ground handling can completely destroy the value of excellent flying characteristics. He would see for himself why the ground handling of passengers and loading is numerically the greatest single source of delay in scheduled operations.

A few of the host of things our designer would learn can be listed:

1. With present designs of cargo compartments, it takes a three-man crew 14 minutes to off-load 1,000 lb. of cargo, and it may take twice as long if it is a mixed cargo of mail, express and baggage, which needs sorting. To correct this condition on domestic aircraft we must have roomy cargo compartments which are accessible in flight to permit pre-sorting of the off-load for the next station.
2. When designing the cargo compartments, the floor level and door should be at standard truck-bed level and/or designed for unloading by a simple conveyor belt.
3. Centre of gravity limitations are altogether too critical in present designs. A much wider range must be provided to facilitate loading.
4. One cabin entrance door is not sufficient through which to handle the off- and on-loading of passengers, the commissary and food service and the movement of cabin cleaning crew.
5. It must be made unnecessary to work through any cargo or other compartment to get at the radio, electrical, instrument or accessory equipment. These must be immediately available by the simple removal of a covering panel and must be arranged to permit easy removal and fast replacement of a defective unit.
6. The fuel tanks must be capable of accepting high rates of flow, preferably by single-point underwing refuelling. Facilities for the flushing of toilets and replenishing of water, alcohol, oxygen, fire extinguisher and hydraulic supplies must be suitably arranged for external servicing.
7. Provision must be made for complete cabin air-conditioning by the simple provision of an external power source.
8. The cabin and cargo doors still require considerable improvement in detail design. It is difficult to understand why a door cannot be made to open and shut a few times per day without going out of adjustment. The wearing parts, such as hinges and door sills, must be quickly and easily replaceable.
9. Cargo compartment linings must be free of the protruding screw heads and raw edges of sheet metal which mutilate passenger baggage.

These are just a few items required for better ground handling facility which must receive thorough examination before the aircraft design even reaches the drawing office. Lack of proper aircraft facilities for ground handling represents a major operating cost increase which can easily be eliminated by thoroughly understanding all the details of the proposed operation before even the writing of the specification commences.

THE MANUFACTURERS.

In any review of airline aircraft in operation one fact is very evident. In the preparation of aircraft specifications both the airlines and the manufacturers have failed to observe, analyse and benefit from past experience.

Why some mistakes are repeated with every new aircraft is difficult to understand. I believe our designers and senior airline

engineers have got too far away from the practical aspect of an aeroplane in operation. They have forgotten the days when a set of overalls or a shop coat was an essential item of equipment in their professional duties.

Perhaps the design staffs stopped getting their hands dirty as a direct result of the necessary over-expansion during the war and perhaps it is the war-engendered economic philosophy which has caused an apparently complete disregard for monetary considerations. Whatever the reasons, the new aircraft are the most expensive ever produced, both in first costs and operating costs.

I want to make it clear that both the airlines and the manufacturers are guilty. The inevitable result is aircraft which require expensive modification programmes before operation can begin and a continuous increased maintenance cost which may completely offset the revenue advantages of increased speed and capacity.

Weight control in manufacture.

There is one outstanding example of poor manufacturing procedure and that is weight estimating during design, and weight control during manufacture.

To the best of my knowledge no aircraft yet produced has met its original weight estimate. We have become so familiar with increases in gross weight or increases in power and gross weight, made necessary by errors in design office weight figures, that it is now almost accepted as a normal condition in the development of a new aircraft.

When an airline operator places orders for a selected aircraft he bases his economic calculations, in large part, on the manufacturer's weight figures. Departure from these figures jeopardises the entire operation of the airline. On North Atlantic operations the weight of one passenger can make the difference between a handsome profit or an operating deficit. It is simple arithmetic to multiply a single round trip fare of £150 × 14 flights per week × 52 weeks per year to obtain a sum total that costs many times as much as proper weight control would have cost in the first place.

When buying aircraft the airline operators would be glad to pay the increased capital costs of sound manufacturing weight estimating and weight control. At the same time the manufacturers would certainly be repaid many times over by freedom from the inevitable modification programme to make overweight aircraft acceptable for operations.

CONCLUSION.

In preparing this talk on aircraft and airlines, the most difficult problem I met was deciding what should be included. I know my selection of the items for discussion has excluded such major factors as aircraft maintenance and overhaul practices or the effect of airport and airport buildings on airline operation but, somewhat sketchily perhaps, I have outlined some of the principles and opinions which are the sources of discussion in Canada. That I am not alone in these opinions can be illustrated by example.

In 1942 my Company started the preparation of a specification for post-war transports. To-day the preliminary version of an aircraft built to that specification has seen several highly successful months of service on the North Atlantic. As a matter of interest I will amplify that statement to some extent.

When the DC-4M North Star was selected as T.C.A.'s major operational type, there existed a lack of design ability in the manufacturing plants in Canada. We were unable to start from scratch and build the aeroplane we wanted; however, we have succeeded to a degree in applying some of the principles discussed in this talk.

I have discussed simplification of the pilot's duties and automatic control. In the North Star we have taken this principle as far as present airway facilities will permit. One example of this is the Rolls-Royce power plant with which the North Star is equipped. With the co-operation and guidance of Rolls-Royce Limited, we have succeeded in making all engine controls entirely automatic, thus greatly simplifying the cockpit control. The propellers are controlled by a single lever, and provision has been made, and equipment purchased, for eventually hooking up the automatic pilot, the aircraft controls and the power plants for operation by radio control.

That the innovations which have been made are successful in their purpose would be endorsed by any of T.C.A.'s Trans-Atlantic flight personnel, and is proved by the record of 100 per cent. completion of all schedules. At the same time we are finding that in the principal items the maintenance and overhaul costs in both man hours and

materials are appreciably lower than our most optimistic estimates.

CANADIAN DEVELOPMENTS.

In the development of her national airlines, Canada is "making haste slowly," yet with great ambition. Our internal domestic and trans-border flight equipment at present comprises well-known, tried and proved aircraft which are operated well within the limits dictated by safety and the type of operation for which the aircraft were designed. In the future, main line services will be operated with pressurised North Star aircraft which will easily maintain Canada's competitive position. With this we are still not satisfied.

After careful consideration of all the practical and economic factors involved, and after thorough and searching comparison with existing and proposed types, a development programme for an advanced passenger transport powered by jet engines is in process, and construction of the prototype is now well advanced at the Toronto plant of A. V. Roe (Canada) Limited. Details of the design specification have not yet been publicly released, but it can be said that, if and when that aircraft flies, it will bring to reality many of the improvements discussed in this paper. It will be built suitable for completely automatic control. It will be fast. It will be simple to operate. It will demonstrate real progress along the road of regularity and safety and, last but not least, it will, I believe, be more economic by any analysis, and by a substantial margin, than any existing airline aircraft.

We of the airlines all look forward to and strive to bring closer, that day when, with clockwork regularity and in supreme safety, our aircraft will carry the air cargoes of a united world. Our convictions differ widely on how to attain it, but nevertheless that day inevitably will come.

To-night you have given me an opportunity to voice a personal Canadian opinion and, most sincerely, I thank you.

A vote of thanks to Mr. Bain was proposed by Sir Frederick Handley Page, C.B.E., F.R.Ae.S., Immediate Past President of the Society and was seconded by Mr. N. E. Rowe, C.B.E., F.R.Ae.S., Vice-President of the Society.

Sir Frederick Handley Page: In many respects it was a pity that there would be no discussion of Mr. Bain's lecture, because something might have been heard about those awful manufacturers—the terrible people who made engines which the aircraft manufacturer had to accept. In spite of the difficulties, however, it could be said that the aircraft manufacturer seemed to be capable of getting over them somehow and making the aircraft fly!

In thinking about those things, one might wonder sometimes whether the far-seeing airline operators, in trying to guide everyone in the right track, had always been able to do so, and perhaps they had led them up the garden path instead!

It would be ill-advised of him, however, under the guise of proposing a vote of thanks, to discuss the lecture and thus seek an advantage over those who no doubt would, on the one hand, like to praise Mr. Bain and, on the other hand, rend him to pieces. Whatever one might say, the lecture was both interesting and stimulating, and well worthy of a high place in the list of papers which had been read before the Royal Aeronautical Society and those which would be given in the future. It was also stimulating to listen to someone who was not afraid to say what he thought about our aircraft and airline operation; and even with the good aircraft he had, and the good experience he had obtained, it was evident from the beginning of the paper that he was not quite so fully satisfied with all those points which the latter part of the paper would seem to indicate.

He had pleasure in proposing a warm vote of thanks to Mr. Bain for a lecture which had been greatly enjoyed by all present.

Mr. N. E. Rowe: He had enjoyed the charming hospitality of Mr. Bain last year at Montreal. He had visited several places in Canada at that time, and wherever he went to talk to airline people he was told that whoever else he met, he must meet Jimmie Bain. And so, at the first opportunity, he did so. Mr. Bain was a very busy man; nevertheless, he had placed enough time at his disposal to exchange ideas, and he was flattered to find that some of his own bore relationship with Mr. Bain's, and they had agreed on a great number of points.

Mr. Bain was at that time looking after the production of the DC-4M Merlin-engined aircraft and he had been greatly impressed by the things he had seen in that connection, as well as by the obvious enthusiasm and forward-looking air progress which was being made. He had also had an opportunity to see something of the new Avro design, which was mentioned during the lecture, and with which he was also greatly impressed.

There was no doubt that Mr. Bain had played a great part in the progress of civil airline operation in Canada and clearly, he was still playing that part. The success of the DC-4M, he was quite certain, owed much to the fact that Mr. Bain had been in it right from the beginning; what he had demanded he had obviously obtained.

The Society would be proud to think that it was in England that Mr. Bain had served his apprenticeship (if one might be permitted to call it that), to the engineering side of civil aviation, and could take much credit for the great things he was doing at the present time.

He had much pleasure in seconding the vote of thanks.

COUNCIL DINNER

After the Lecture a dinner was given by the Council of the Society at 4 Hamilton Place, at which the following were present:—

J. E. Adams, London Manager, Air France; Lt. Colonel A. V. Agius, M.C., Trade Commissioner for Malta.

James T. Bain, Lecturer, Director of Engineering and Maintenance, Trans-Canada Air Lines; Air Commodore F. R. Banks, C.B., O.B.E., F.I.P., M.S.A.E., F.R.Ae.S., Member of Council, R.Ae.S.; Sir John S. Buchanan, C.B.E., A.M.I.Mech.E., F.R.Ae.S., Vice-President, R.Ae.S.; Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Member of Council, R.Ae.S.

S. Camm, C.B.E., F.R.Ae.S., Member of Council, R.Ae.S.; Colonel G. M. Carrie, O.B.E., Canadian Defence Research Liaison Officer; Air Vice-Marshal Sir Conrad Collier, K.C.B., C.B.E., Controller of Technical and Operational Services, Ministry of Civil Aviation; Dr. H. Roxbee Cox, B.Sc., D.I.C., F.R.Ae.S., President, R.Ae.S.; W. H. Cumming, A.F.R.Ae.S., Chairman, Air Charter Association.

Dr. G. P. Douglas, O.B.E., M.C., F.R.Ae.S., Member of Council, R.Ae.S.; G. H. Dowty, F.R.Ae.S., Dowty Equipment Ltd.; A. G. Elliott, C.B.E., M.S.A.E., F.R.Ae.S., Member of Council, R.Ae.S.; Gerard d'Erlanger, Chairman, British European Airways.

W. S. Farren, C.B.E., F.R.S., F.R.Ae.S., Member of Council, R.Ae.S.; Sir A. H. Roy Fedden, M.B.E., D.Sc., M.I.Mech.E., M.S.A.E., F.R.Ae.S., Past President, R.Ae.S.

G. S. Gibson, District Traffic Manager, Trans-Canada Air Lines; A. Gouge, B.Sc., F.R.Ae.S., Past President, R.Ae.S.

Professor A. A. Hall, M.A., F.R.Ae.S., Member of Council, R.Ae.S.; S. Scott Hall, A.C.G.I., M.Sc., D.I.C., F.R.Ae.S., Member of Council, R.Ae.S.; R. E. Hardingham, O.B.E., A.F.R.Ae.S., Secretary, Air Registration Board; E. W. Hives, F.R.Ae.S., Rolls-Royce Limited; J. E. Hodgson, Hon.F.R.Ae.S., Honorary Librarian, R.Ae.S.

Captain H. Spry Leverton, O.B.E., Regional Director of K.L.M.

Dr. J. G. Mallock, Scientific Liaison Officer, Canadian National Research Council; P. G. Masefield, M.A., F.R.Ae.S., Member of Council, R.Ae.S.; Air Vice-Marshal R. E. McBurney, C.B.E., Senior Canadian Air Force Liaison Officer.

R. E. Norton, O.B.E., East African Commissioner (Civil Aviation).

Sir Frederick Handley Page, C.B.E., R.Ae.S., Past President, R.Ae.S.; W. G. A. Perring, F.R.Ae.S., Vice-President, R.Ae.S.; Captain J. Laurence Pritchard, F.I.Ae.S., Hon.F.R.Ae.S., Secretary, R.Ae.S.

P. Ranganathan, Deputising for High Commissioner for India; N. E. Rowe, C.B.E., B.Sc., D.I.C., F.R.Ae.S., Vice-President, R.Ae.S.; J. G. Roxburgh, Grad.R.Ae.S., Secretary of Graduates' and Students' Section, R.Ae.S.; T. W. Royle, C.V.O., M.B.E., President, Institute of Transport.

S. G. Slack, Civil Air Liaison Officer for South Africa; J. Hanford Stevens, United Kingdom Representative for Australian Aviation.

Captain C. F. Uwins, A.F.C., O.B.E., F.R.Ae.S., Honorary Treasurer, R.Ae.S.

Dr. H. C. Watts, F.R.Ae.S., Member of Council, R.Ae.S.; Group Captain C. A. Wilcock, M.P., Chairman, Civil Aviation Section of Parliamentary Party's Transport Group; L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor, R.Ae.S.

THE ROYAL AERONAUTICAL SOCIETY

The 743rd Lecture read before the Society—on 18th December 1947 at the Institute of Civil Engineers, Great George Street, S.W.1. In the chair, the President, Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S.

THE DESIGN AND WORK OF THE FARNBOROUGH HIGH SPEED TUNNEL

by

Professor A. THOM, M.A., Ph.D., and W. G. A. PERRING, F.R.Ae.S.

Professor Thom obtained his degree at Glasgow University in 1915. He worked in various civil engineering and aircraft firms until 1922 when he rejoined Glasgow University as a lecturer in civil engineering and also as a lecturer on aeronautical subjects. In 1939 he joined the Aero Department of the Royal Aircraft Establishment and was responsible for the experimental work on the High Speed Tunnel from 1940-1945. Since 1945 he has been Professor of Engineering Science at the University of Oxford.

Mr. Perring is Director of the Royal Aircraft Establishment and Director-Designate of the new National Aeronautical Establishment which is to be at Bedford. The design and planning of the R.A.E. High Speed Tunnel and the co-ordination of the engineering work involved were in his charge.

INTRODUCTION.

Historical Review.

THE importance of the effects of compressibility on the performance and behaviour of high speed aircraft has been appreciated for a great many years, but in this country it was not until 1937 that serious attention was given to the design of a wind tunnel that would enable the study of compressibility to be undertaken by tests on models of reasonable scale. Prior to 1937 the work which had gone on had established the characteristics of a few aerofoils and simple shapes; at Farnborough the work mainly related to the testing of high tip speed propellers, while at the National Physical Laboratory tests had been made of a two-dimensional character on aerofoils, these tests being made in a small wind tunnel driven on the injector principle, by air discharged from a high pressure reservoir.

Towards the end of 1937 sketch plans were prepared for a high speed wind tunnel having a working section 10 ft. by 7 ft. and capable of a maximum speed of 600 m.p.h. The preliminary design was for a tunnel having a single return circuit, powered by a 4,000 h.p. motor and cooled by a radiator located in the settling chamber. The tunnel was estimated to cost about £200,000 and, although at the time, having regard to the wide range of work that would have to be undertaken, it was considered that a tunnel of working section 10 ft. by 7 ft. represented the smallest tunnel that would meet the requirements, alternative plans were prepared for a tunnel of working section of 7.5 ft. by 5.5 ft., which it was estimated would cost about £125,000. Towards the end of 1937 it was suggested by Mr. Relf that we should consider a tunnel of symmetrical design on lines similar to the C.A.T. of the National Physical Laboratory. By adopting such a design strength problems would be greatly simplified and it was anticipated that the distribution of flow in the working section would also be improved.

A scheme based on the annular flow principle was prepared early in 1938, and this proved attractive from an engineering point of view; the design was reasonably compact, the structural problems were considerably eased and, as will be seen later, by incorporating the cooling system in the structure the arrangement provided not only an elegant solution of the cooling problem, but also enabled the shell to be fabricated from relatively thin sheets. Having accepted the symmetrical design of tunnel, it was decided to construct and make tests on a 1/16 scale model, so as to settle a number of the design points before settling finally the details of the main design. Construction of the model was started about March 1938 and it was hoped to complete its manufacture and be ready for

test by the autumn of 1938. This proved too ambitious a programme, but the model tunnel was completed and the tests were started during March 1939.

In the meantime, because of the delay that would inevitably ensue if the main design were allowed to await the outcome of the model tests, the whole position was reviewed at a meeting during July 1938, under the chairmanship of Mr. W. S. Farren. This meeting decided that work on the main tunnel should proceed immediately. Accordingly, discussions began with various contracting firms during August 1938, it being recognised by both sides in all these discussions that many points concerning the final design must await, or might be modified as a result of, the model work.

A contract for the main structure was placed with the firm of Sir William Arrol in February 1939 and with J. and E. Hall for the refrigeration equipment and cooling system. Later, during 1939, contracts were placed with the British Thomson Houston Co. for the main motor, shafting and fan; with Messrs. Holst for the main building to house the tunnel and its equipment; with Browett Lindley for the evacuation and compressor equipment; and with Sir Howard Grubb Parsons and Co. for the tunnel balance. The tunnel was completed and ready for running by August 1942 and it was officially opened by Col. the Rt. Hon. (now Lord) J. J. Llewellyn on Friday, 6th November 1942.

But for the very willing help and co-operation we had from all the main contractors, the tunnel could never have been built in the time and in paying a tribute to them, we should also like to add a word of appreciation for the work of (now Professor) A. A. Hall, J. Nixon, G. F. Midwood and K. Wilkinson, members of R.A.E. staff and members of the hard-working team that was concerned with the tunnel design. It would also be unfair to the many firms and individuals who worked so hard on the project if we failed to point out that the tunnel began to work from the day it was completed. All the machines, the complicated automatic controls on motors, on oil, on cooling, and so on, the automatic balances, the valves and indicators, worked from the first and with only minor modifications, have continued to work. This was only made possible by a degree of enthusiasm, determination and co-operation which can seldom have been equalled. The achievement is the more remarkable when the magnitude of the undertaking, its complexity, and the difficulties brought about by the war are taken into account.

In the present paper it is proposed to sketch briefly some of the considerations and details concerning the tunnel design and construction, to discuss the operation of the tunnel and the interpretation of the results, then review the work of the tunnel and conclude with some remarks on its work in the future.

PRELIMINARY CONSIDERATIONS.

The tunnel was to be designed to achieve a speed of 600 m.p.h. with an input power of 4,000 h.p., this horse-power being the maximum that could be made available at the time of the design.

Calculations, see Appendix I, had led us to hope that a power factor of 0.21, *i.e.* the ratio of the fan power to the rate at which kinetic energy is passing through the working section, should be possible, provided that the walls of the tunnel could be maintained aerodynamically smooth. For the size of tunnel under consideration, aerodynamic smoothness corresponded to an equivalent roughness height not exceeding 0.003 in. in the working section, and not exceeding 0.008 in. in the return circuit.

To allow a margin for roughness and other incidental losses, a more conservative power factor of 0.25 was assumed as the basis of our design calculations and, on this assumption, a speed of 600 m.p.h. and fan power of 4,000 h.p. corresponded to a working section pressure of about 1/6 of an atmosphere absolute.

It was clear that the main tunnel shell would have to be designed to withstand a vacuum and in deciding the details of the structure, the stability of the shell under this collapsing load became a matter of first importance. Rough calculations also indicated that with an input power of 4,000 h.p., dissipated almost entirely in overcoming the frictional resistance of the walls, and therefore in causing heating of the air stream, the initial rate of increase of air temperature would be large. In the absence of any arrangements to extract this heat, the initial rate of rise of the air temperature would be about 4°C. per second and since, too, the transfer of this amount of heat from the air to the outer shell demanded a temperature difference between the air and the shell of nearly 60°C., it was clear with the outer shell at, say, 15°C., that the temperature of the

air in the return circuit after a short period of running would rise to about 75°C. Under these conditions and with the tunnel operating at 600 m.p.h., this would correspond to a working section temperature of approximately 40°C.

These conditions, besides being embarrassing from an operating point of view, had the grave disadvantage of increasing the speed of sound of the air in the working section and since for compressibility work it is the operating speed as a fraction of the speed of sound, *i.e.* the Mach number, and not the absolute speed that is important, it was necessary to provide the tunnel with effective cooling arrangements.

The possibility of employing the walls of the tunnel as cooling surfaces was investigated, see Appendix 2, and it was found that provided these walls and the inner walls could be maintained at about −5°C., the tunnel would operate with a static air temperature in the working section of 15°C. when the air speed corresponded to 0.8 Mach number and the input power was 4,000 h.p.

In the tunnel as designed, cooling jackets were formed as an integral part of the structure and since they increased the depth, and therefore the inertia of the shell, the jackets played an important part in stabilising the shell against the collapsing loads when under vacuum.

In laying out the tunnel consideration was also given to the need to achieve a reasonably low turbulence of the air stream in the working section and with this in mind, the rate of expansion of the diffuser was arranged nowhere to exceed 7° total angle, while a contraction ratio of 7 to 1 was provided. The design also allowed for the fitting of a one in. mesh honeycomb of five calibres depth, followed by a settling chamber 9 ft. long.

With this configuration it was hoped that the flow distribution would be good, and the turbulence level in the working section would not exceed 0.3 per cent. Judged by modern standards (made possible by the use of fine gauge screens) this would now be regarded as a comparatively high value, but when the tunnel was designed (which was nearly ten years ago) it was considered reasonable. Low turbulence requires a large contraction ratio and it should perhaps be noted that the symmetrical design of tunnel, which came to be adopted, does not lend itself to the use of very large contraction ratios since any increase in this ratio gives rise to a large increase in the diameter of the outer shell, the outer shell having to embrace a settling chamber and a return circuit of the same cross section as the settling chamber, and this in a vacuum vessel results in much thicker shell plates having to be used, and therefore, correspondingly greater complexity of design and manufacture.

MODEL EXPERIMENTS.

Having settled the general form of tunnel design, there remained a large number of detail points to be decided. For example, it was important to ensure a good flow distribution in the working section; the tunnel had to be constructed in steel and any major modifications in design, although not impossible, would nevertheless have been costly in time and money.

Again, although calculations had indicated that the cooling should be adequate, little or no work had been done at that time to establish the heat transfer coefficients at high speeds. A check of the cooling seemed desirable and furthermore, when deciding the detail design of the jacket system, the local heat transfer coefficients at all points around the tunnel circuit had to be established, so as to ensure when subdividing the jacket system and fixing the rate of coolant circulation that each section carried its proper share of the cooling load.

The tunnel fan design was also critical, as both the fan tip speed and fan solidity were high and, although at the time it was appreciated that the adoption of a two-stage arrangement would simplify the design problem, the fitting of a two-stage fan would have introduced increased engineering complexity. A check, therefore, on the fan design seemed desirable. These and other considerations led to the construction of a 1/16 scale model of the tunnel.

The model work was required to provide a quick check on the numerous design features so that the main design could proceed and in order to save time in constructing the tunnel, extensive use was made of existing plant. Thus an existing 70-80 h.p. electrical motor was used to drive the fan, the motor being coupled through a 12.5:1 gearing so that it could drive the fan shaft at speeds up to 15,000 r.p.m.

In mounting the gearbox, means were provided to measure the torque transmitted to the fan. The cylindrical portion of the outer shell of the tunnel and the tunnel ends

were made from cast iron, the end pieces being made readily detachable. The inner shell was also built up from castings made from phosphor bronze. All the castings were machined, both inside and out, on the wind-swept side, to provide a smooth finish and on the other side, to make provision for the cooling jackets which were formed in the casting and completed by the fitting of cover plates.

Figure 1 is a general arrangement drawing of the model showing the form of construction adopted. It indicates the provision made for cooling jackets and also shows the openings—one on the top and the other on the bottom—through which it was possible to obtain access to the working section.

Coolant to the inner jackets entered the tunnel through the inner shell supporting members at the fan end, while the supports at the settling chamber end were arranged to carry the pressure tubing and electrical leads connected to the measuring equipment.

The model provided a check on the general distribution of flow in the working section and at several sections around the circuit of the tunnel; it also provided a check on the power factor and enabled tests to be made to measure the effect on the distribution when a wing was introduced into the working section. Measurements were also made to establish the rate of cooling at various points around the tunnel circuit and, the temperature distribution of the air in the working section was measured.

In the design of a high speed tunnel, the temperature distribution of the air in the working section is almost as important as the velocity distribution, since variations in either temperature or velocity will modify the local Mach number and therefore will influence the behaviour of the air stream as it passes over the object under test. The model also provided a check on the fan design and this work was particularly valuable when, at a later stage, it became desirable to adjust the blade setting and reduce the centrifugal stresses in the fan blades by reducing the rotating tip speed of the fan from 800 ft./sec. to 720 ft./sec., while at the same time the fan absorbed the full 4,000 h.p.

At a later stage the model was used to investigate a slow period cyclic disturbance of flow, which was observed to be present and which produced unsteadiness of balance readings in the main tunnel when it was brought into operation. Exploration by hot wire technique showed the disturbance to be rather complex. Designating position round the annular return space in degrees, the pulsation manifested itself there by showing a cyclic variation so that when the speed was a maximum at 0° and 180° it was a minimum at 90° and 270°. After $2\frac{1}{2}$ seconds (at $M = 0.7$), conditions were reversed, the period being about three times longer than the time taken for a complete circuit of air round the tunnel. The origin of the phenomenon is probably to be found in the first expansion after the working section, where the section is changing from rectangular to circular.

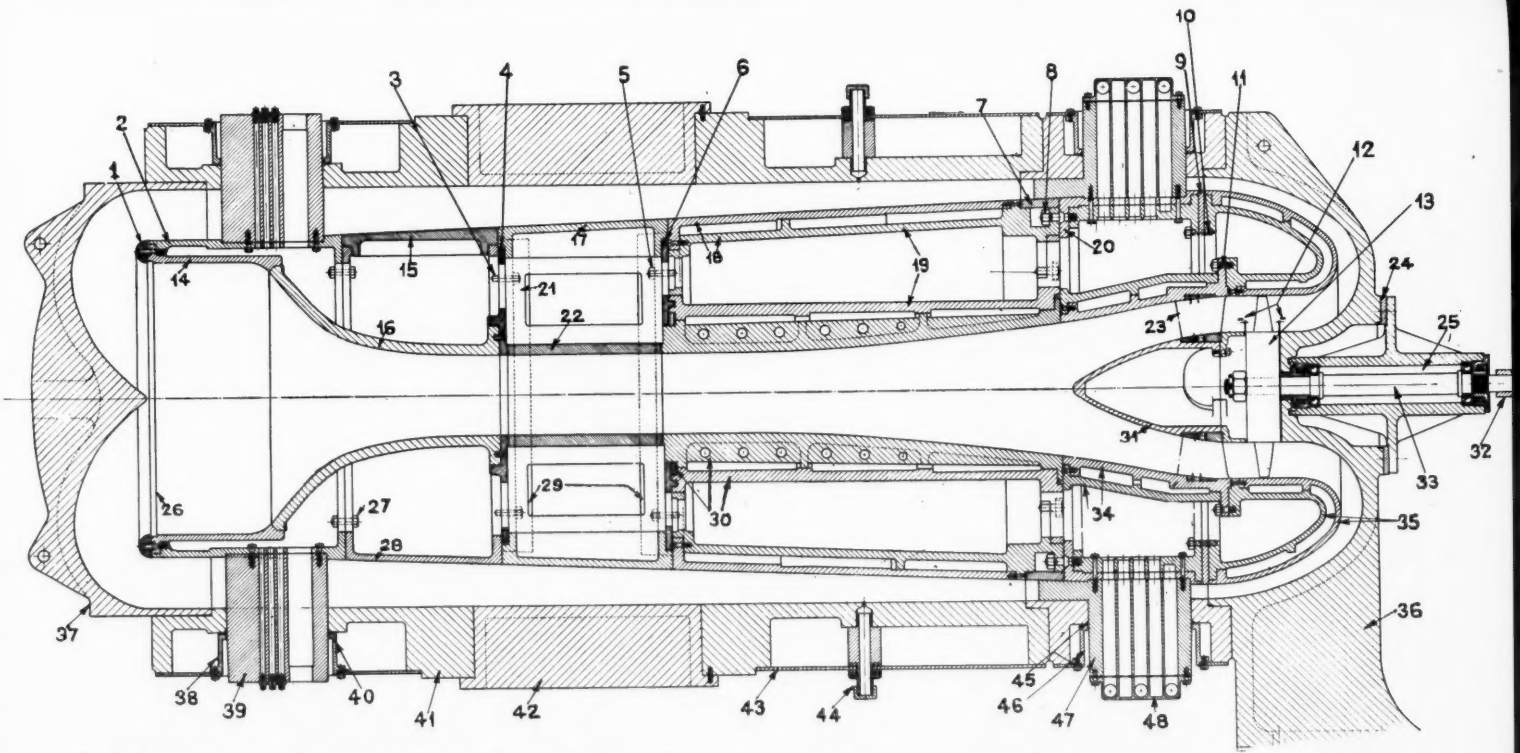
The same phenomenon was found from the model, but while there it was possible to cure it completely by mixing vanes in the return circuit; this method was only partially successful in the full size tunnel.

In parallel with the model work just described, a good deal of other work was put in hand to check not only the broad features of the design, but also the detail points affecting the construction and assembly. For example, before even the 1/16 scale model was built, a small water channel, representative of one-half of the tunnel, was constructed and used to study the flow conditions around the tunnel circuit. This work provided a valuable check on the flow along the diffuser and into the fan, the flow at the high speed bend downstream of the fan and also, at the low speed turn into the settling chamber.

To keep the overall diameter of the tunnel as small as possible, the radius of turn at the low speed end had been made very small. It was anticipated that conditions at this corner would be critical and, as will be seen later, annular cascades were eventually provided to prevent flow separation after the turn.

Again, before settling the cooling arrangements, several small experimental rigs were set up and an elaborate series of tests were undertaken on various cooling arrangements on our behalf by Messrs. J. and E. Hall. At the same time we undertook an extensive series of tests to study the corrosion problem; this work enabled the choice of coolant to be decided—it also threw light on several points which were later embodied into the design, as well as providing data on which the subsequent control of the acidity of the coolant was based.

Then again as regards the structure, we have seen in discussing the power factor how important it was to maintain the air-swept surfaces of the tunnel "aerodynamically



1. Fastening ring.
2. Support section.
3. Studs.
4. End plate.
5. Studs.
6. End plate.
7. Fastening ring.
8. Studs.
9. Joint plate.
10. Studs.
11. Studs.
12. During assembly it is important that clearances of .03 in. are obtained.
13. Fan.
14. Settling chamber.
15. Manhole.
16. Contraction cone.
17. Outer cover.
18. Outer casing and water jacket.
19. Casing.
20. Water jacket.
21. Working section.
22. Inner covers.
23. Guide vanes.
24. Joint plate.
25. Drive.
26. Honeycomb.
27. Bolts.
28. Casing.
29. Fastening rings.
30. Outer section and water jacket.
31. Spinner.
32. Drive.
33. Drive.
34. Inner casing and water jacket.
35. Water jacket.
36. Driving end cover.
37. Cast iron end cover.
38. Outer casing seal.
39. Support.
40. Rubber joints.
41. Outer casing.
42. Manhole cover.
43. Outer casing water jacket.
44. Alternative vacuum connection.
45. Rubber joints.
46. Outer casing seal.
47. Support.
48. Header.

Fig. 1.
Model high speed wind tunnel (Scheme 2). Detail arrangement of inner shell.

smooth" and, being aeronautical engineers, you will appreciate that while it is essential to avoid actual roughness, it is equally important, especially in those sections where the air speed is high, to avoid any undue waviness.

The form of construction proposed required that the cooling jackets should be welded on to a relatively thin mild steel plate; experiments were undertaken to consider how distortion of the plates might best be avoided during the welding and fabrication process.

The work was done by Sir William Arrol and the method tried, which proved successful and which was finally adopted, was one in which the flanges of the channels which formed the jackets were slightly toed in by arching the web. The welding tended to remove the arching of the web, leaving the surface of the main plate flat and free from distortion.

We have only been able to refer to a few of the experimental items which were undertaken before the work of construction started; we are sure it will be appreciated what a large number of detail points require to be settled in this way when designing a piece of equipment which in many ways is as "experimental" as the work for which it is being built.

GENERAL DESCRIPTION OF TUNNEL.

It has already been stated that the tunnel is of symmetrical design; the main strength shell of the tunnel comprises a cylindrical structure having hemispherical ends and built into this shell, is a structure forming a settling chamber, working section and diffuser cone along the axis of the shell, and an annular return passage around the walls.

These main details are shown diagrammatically in Figs. 2 and 3. The outer shell of the tunnel is 37 ft. diameter and 130 ft. long, and this shell is supported on pairs of supports spaced 90 ft. apart. The inner shell is supported from the outer shell by two sets of streamlined strut supports, each set comprising six struts, built in near the ends of the cylindrical portion of the outer shell.

STRUCTURE.

Details of the shell construction can be seen from Fig. 4; the outer shell plates are 9/16 in. thick and the cooling jackets were formed by welding on 12 in. by 4 in. channel sections spaced 11¼ in. apart, the space between the channels being closed to complete the jacket by a cover plate welded to the channel webs. Holes were provided in the channel flanges, so that the coolant could be circulated up one jacket and down the next.

The outer shell was built up in sections 8.5 ft. long, each section comprising six plates, complete with their cooling jackets. The ends of each section terminated in a main stabilising ring, the ends being bolted to this ring by means of countersunk bolts so as to form a flush, smooth wall on the windswept surface. To ensure freedom from eccentricity, the main stabilising rings, which were of I-section and of built-up welded construction, were assembled as rings and finished by machining the inner flanges before leaving the works.

The design of most of the inner structure followed closely the lines of the outer structure, except that the walls were mainly formed of 3/8 in. plate; the ends of the inner structure terminated in castings and the working section was also fabricated from castings, all the air swept surfaces of these castings being machine finished to ensure their accuracy and provide a smooth surface.

Expansion of the outer shell was provided for by anchoring the tunnel at one support and restraining it in direction at two of the other supports, while it was free to move both longitudinally and laterally at the fourth support. Freedom of expansion between the shells was achieved by merely fixing the inner shell at one end and leaving it free to slide at the other.

To protect the surfaces from corrosion and to avoid the use of paint on surfaces that were to be scrubbed by the air, and repeatedly subject to pressure conditions varying from a vacuum to four atmospheres absolute, the surfaces were cleaned and aluminised by metal spraying.

The working section of the tunnel, measuring 10 ft. by 7 ft., was formed of castings and was machined throughout. It was provided with windows on each side and with turntables top and bottom, as well as with a number of other readily movable portions, to facilitate its adaptation to a wide range of work.

A 15 ft. length of working section was provided and over the 15 ft. the height was increased from 7 ft. to 7 ft. 2 in., giving an expansion of 2½ per cent. in area to compensate for the increasing boundary layer thickness.

The pressure in the working section was maintained the same as in the "dead" space enclosed between the tunnel axis and the

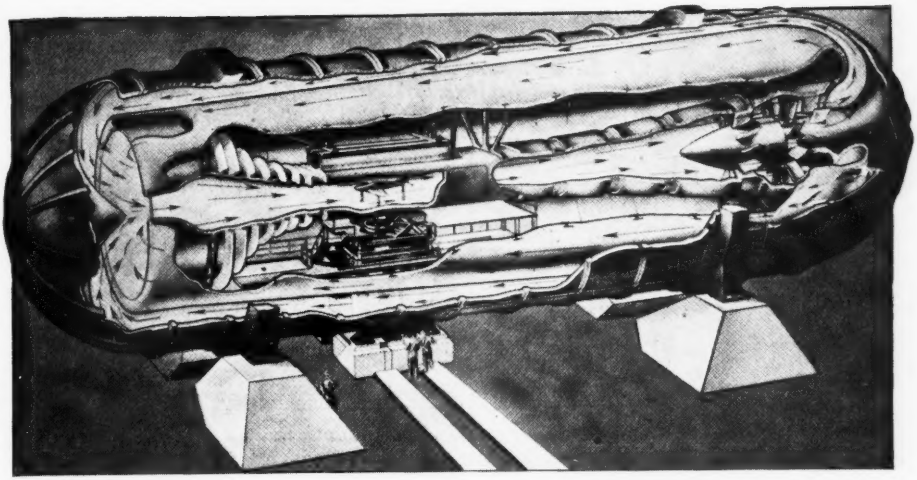


Fig. 2.
Pictorial view of high speed tunnel.

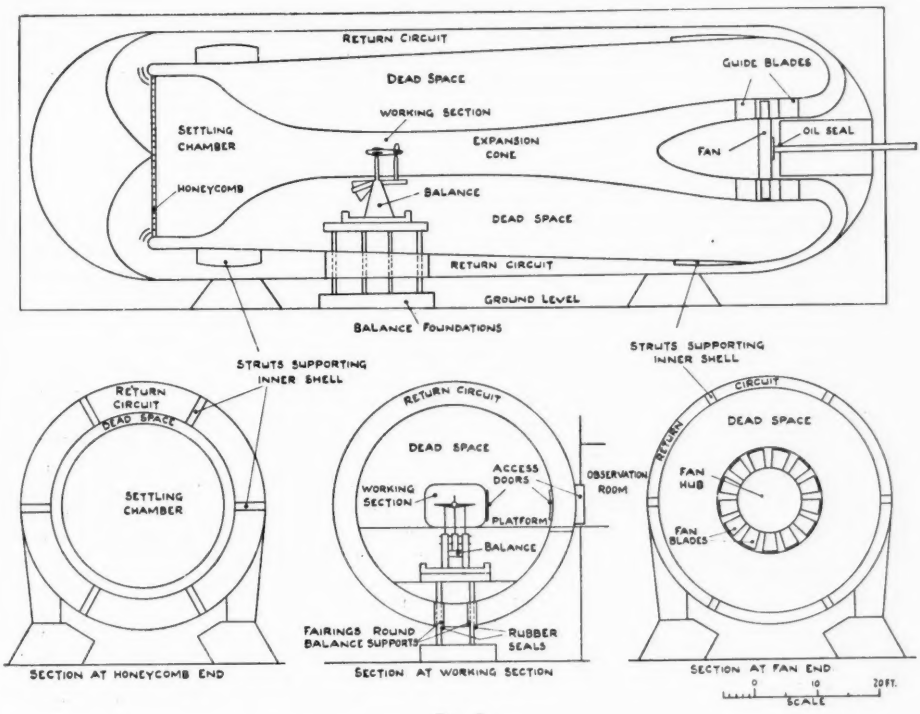


Fig. 3.
General arrangement of high speed tunnel.

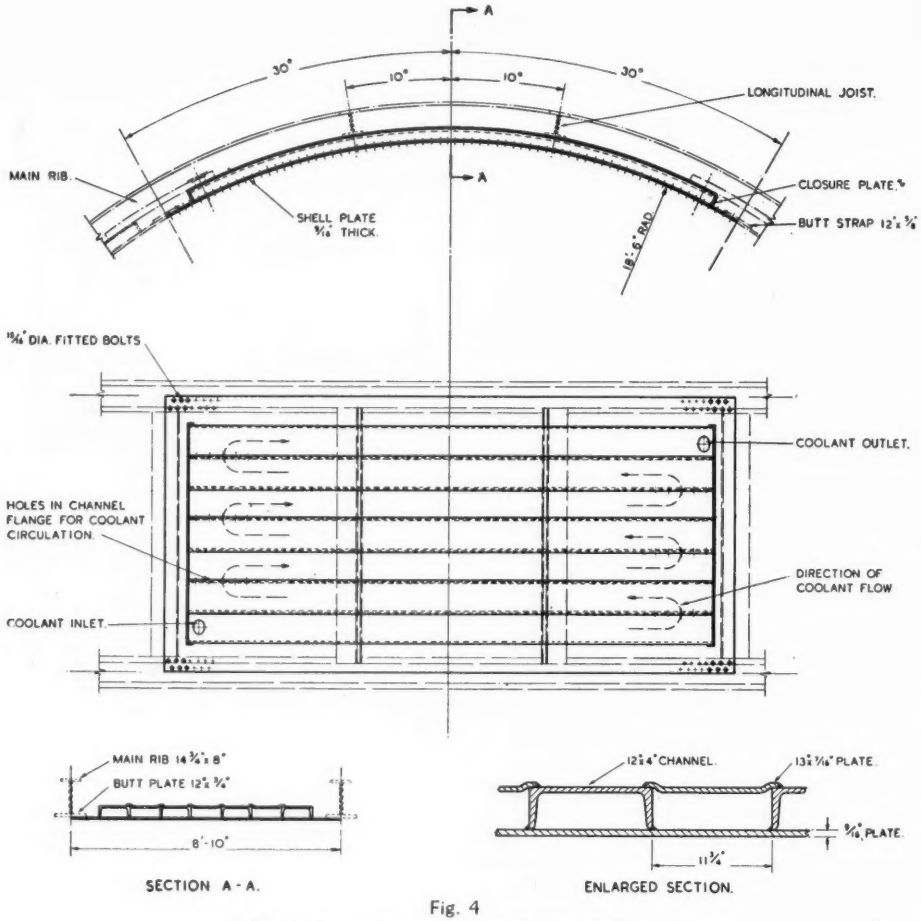


Fig. 4

R.A.E. high speed tunnel—typical outer shell panel.

return circuit, and to do this the working section was vented to the dead space at the downstream end by means of 38 holes, each 2½ inches diameter.

Access to the working section was by means of three flush fitting doors, each 7 ft. by 7 ft., the door in the outer shell being designed to withstand a load of 140 tons, corresponding to the load when the tunnel was run at its highest operating pressure, while the inner doors each opened into the dead space on to a working platform built around the working section.

Windows were provided through the sides of the inner and outer shells forming the return circuit, to match the windows in the working section, and these have been fitted with glass so that it is possible to view the model under test from outside the tunnel.

Similar openings were also provided in the two outer shells vertically above and below the working section, but so far no steps have been taken to fit these openings with glass for observation purposes.

COOLING.

The tunnel is cooled by circulating brine maintained below 0°C. through the jackets formed on the walls of the tunnel circuit. As it was expected that full power operation would never exceed two to three hours on any one day, it was possible by cold storage

arrangements to avoid the heavy refrigeration load that would otherwise have been necessary had the full power output of the tunnel been dealt with on a continuous basis.

Details of the cooling system can be seen from Fig. 5. Four 65 h.p. two-stage ammonia compressors are provided, delivering at about 170 lb./in.^{2}. The high pressure ammonia vapour from the compressors first passes to a condensor, where it is cooled and condensed; it then passes through a reducing valve to brine coolers and finally, returns to the compressors.

On the brine side the system is subdivided into two sections, one to deal with the lower half of the tunnel and the other, with the upper half. The two systems are independent and are separately vented so as to reduce the hydrostatic head imposed on the tunnel structure. Two storage tanks, each containing about 240 tons of calcium chloride brine, are arranged at suitable levels and are fed with cold brine from separate brine coolers. The brine from the storage tanks is circulated by means of pumps through 46 parallel circuits, which can be separately controlled, to obtain the best cooling conditions in the tunnel. The circulation is by means of 7 h.p. centrifugal pumps and thermostatically controlled mixing valves are arranged so that cold brine from the reservoirs, and warm brine from the jackets, can be mixed to produce the required circulating temperature, which can thus be varied according to the load to maintain the air in the tunnel at constant temperature.

A small quantity of sodium dichromate, 0.5 gms./litre, was added to the brine as the result of the experimental work already discussed, and this has been found effective in preventing excessive corrosion.

Water was used for the compressor intercoolers and the ammonia coolers, the water being pumped to a spray pond and cooled before re-entering the cooling system.

Air drying and cleaning.

While it is important to cool the tunnel, it is equally important to dry and clean the air entering the tunnel. The presence of moisture in the air is known at the high local speeds set up around the model to give rise to condensation shocks and these shocks, by modifying the flow, introduce uncertainties in the interpretation of the work. Furthermore, the moisture, on coming into contact with the cooled tunnel walls, would condense and on occasions might have frozen; it would therefore have been a source of trouble, giving rise to the risk of corrosion, or of

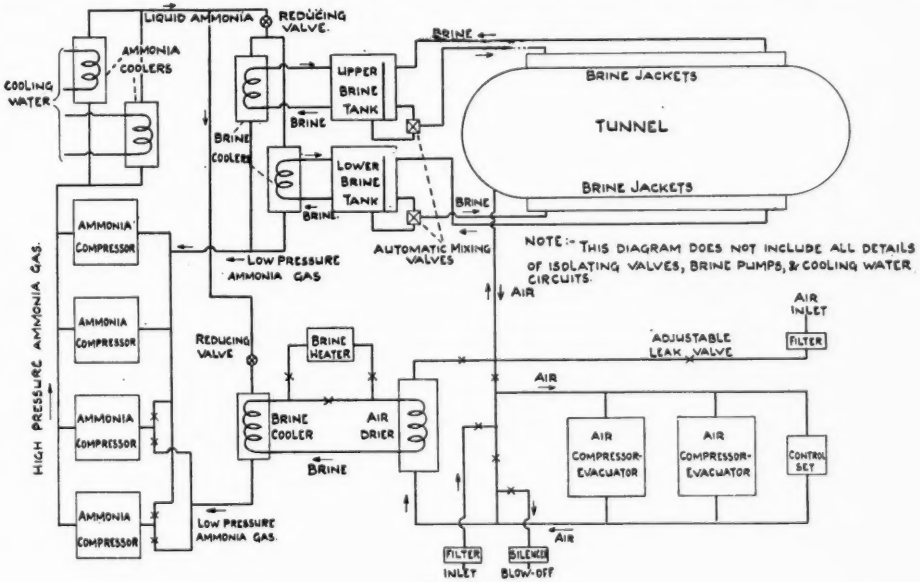


Fig. 5.

Diagram of compressor and refrigerator circuits.

danger to the model under test since the ice formed on freezing might be detached from the walls and circulate around the tunnel at high speed.

Equally important was the need to remove all traces of dust and small foreign bodies from the air entering the tunnel since again, these, by sand-blasting the model, would cause the same troubles as the presence of ice particles. Accordingly all the air entering the tunnel, after filtering, was passed through an air drier. The drier was supplied from a separate brine cooler fed from the same ammonia coolers as the tunnel brine coolers, although this brine circuit was operated at a slightly lower temperature than the others, to ensure that the moisture content of the air was well below that at which condensation could take place inside the tunnel.

To defrost the drier, an electrical brine heater was provided and warm brine could be circulated through the air drier until the ice formed on its pipes was melted.

Again, a small air conditioning plant was installed in the tunnel room to avoid condensation on the brine pipes and on the outside of the tunnel.

FAN DESIGN AND MANUFACTURE.

As it transpired, the fan proved to be one of the most difficult items to design and manufacture. Although some consideration was given to a two-stage design, a single-stage fan was chosen and the basis of the design has been set out briefly in Appendix 3.

Originally the fan, which was 16 ft. diameter, was intended to operate at 960 r.p.m., corresponding to a rotational tip speed of 800 ft./sec., but subsequently, after detailed examination and some difficulties in manufacture had been encountered, a model check was made and the fan speed was reduced by about 10 per cent. To ease the design guide blades were fitted upstream of the fan to introduce pre-rotation into the air, the fan removing the rotation and, in fact, reversing it, leaving some residual rotation in the air stream to be removed by the straighteners at the back of the fan, and by the guide vanes which formed the supports to the inner shell.

Details of the fan design can be seen from Fig. 6. The fan hub, which was of built-up construction, was 9.6 ft. diameter; the hub centre was a forged disc machined from 50 tons alloy steel, while the blades, which were of hiduminium R.R.56, were secured to the hub by means of sockets machined from 55/65 tons steel. Side plates of R.R.56 carrying cowling segments of the same material, formed a fairing which enclosed the blade roots and completed the hub.

The fan had 13 blades so as to avoid coincidence with the twelve pre-rotation guide blades fitted ahead of the fan, or with the six straighteners at the rear, each blade having a finished overall length of 5 ft. 9 in. and a blade width of 26.4 in.

The blades, which were forged, were outside any experience of similar forgings and considerable difficulty arose not only over the forging, but also in the heat treatment and machining stages, and this resulted in a number of blade forgings having to be scrapped before a satisfactory process of manufacture was developed.

To overcome the main forging difficulties, the High Duty Alloy Company, which did the work, increased the size of the blade ingot up to 1,200-1,400 lb. and delivered the rough forging, weighing about 860 lb., to the British Thomson Houston Company which, after turning a shank and trunnion, passed it to the Pressed Steel Company at Oxford, for rough kellering to within $\frac{1}{4}$ in. all over of the finished size. The blades had to be kellered because they were outside the capacity of the normal blade cutting machinery and heat treatment had to be delayed until after the rough kellering stage, because heat treatment of the mass of material forming the boss caused large stresses to be set up in the material.

These internal stresses were further relieved by drilling a 3 in. diameter hole up the centre of the thick portion of the boss.

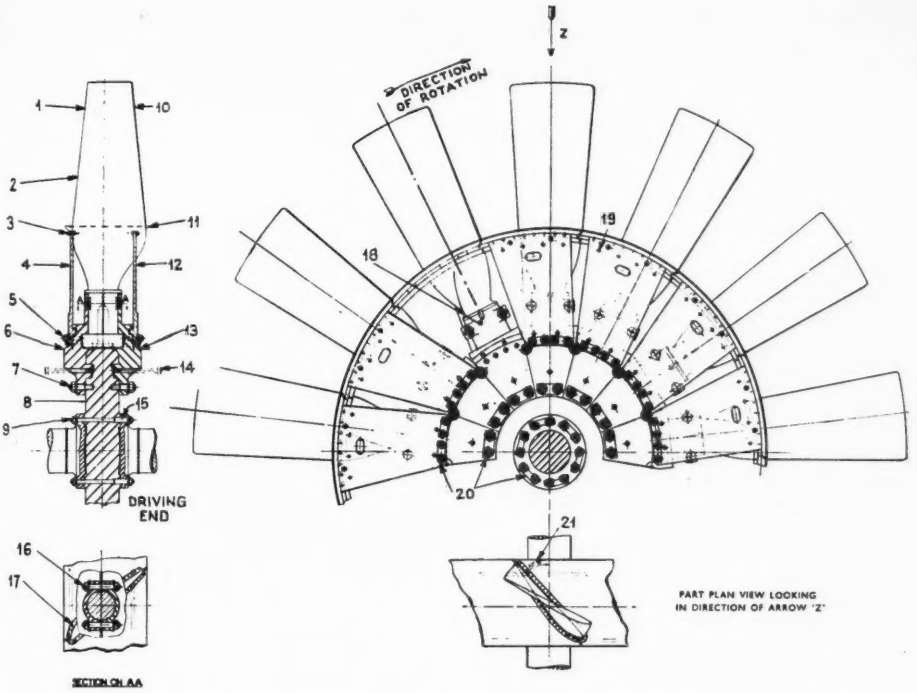
Heat treatment after rough kellering, of course, caused distortion and made it necessary to reset each blade before final kellering.

The blades were then hand finished by means of surface grinders and after removal of the temporary trunnions, they were assembled into the hub and the blade tips machined to their final radius. Individual blades were then weighed; each blade weighed about 320 lb. and the lightest one was chosen as the master blade, all blades being carefully balanced against the master.

The blades were then polished and anodised.

To ensure balance the entire hub was assembled in stages and at each stage it was both statically and dynamically balanced, the hub being run up to 960 r.p.m. at the makers' works to check dynamic balance.

Final balancing of the fan with the blades in position was undertaken on assembly in



1. Leading edge of b'ade.
2. Fan blade hiduminium R.R.56.
3. Studs for securing cowling segment 55/65 ton steel.
4. Cowling bracket (front) hiduminium R.R.56.
5. Studs for securing cowling bracket 55/65 ton steel.
6. Half socket 55/65 ton steel.
7. Studs for securing half sockets 55/65 ton steel.
8. Fan hub alloy steel forged disc. 50 tons minimum.
9. Coupling bolts 55/65 ton steel.
10. Trailing edge of blade.
11. Cowling segment hiduminium R.R.56.
12. Cowling bracket (rear) hiduminium R.R.56.
13. Half socket 55/65 ton steel.
14. Forcing off screws for half sockets.
15. Coupling bolts fitted at this end.
16. Studs for clamping half sockets together 55/65 ton steel.
17. Sealing plates round fan blade duralumin.
18. Key for locating position of fan blade.
19. Holes for balancing purposes.
20. Locking plates for nuts.
21. This angle is 43°—51 where centre line of blade projects through cowling segment.

Fig. 6.

General arrangement drawing of fan.

the tunnel and an apparatus which was, in effect, a seismograph was designed for this purpose. It recorded the components of the horizontal movements of the bearing relating to two axes fixed in the shaft. When x/n is plotted on y/n for varying fan speeds (n) a circle passing through the origin should result. Actually, the circle did not pass through the origin, but when different out-of-balance masses were added, each giving an approximate circle, all these intersected roughly in one point. The explanation was that the shaft, which passed through three bearings, had a very slight bend. A minute adjustment to one of the couplings put the matter right. It was then found that the manufacture of the fan had been done so carefully that the addition of a small mass sufficed to reduce the vibrations, even at critical speeds, to a negligible minimum.

A great deal of consideration was given to the question of the fan clearance, since it was desirable from an efficiency point of view to reduce the running clearance to a minimum. The tunnel shell in the vicinity of the fan was machined to be truly circular, and means were provided for centring this section so that its axis coincided with the axis of the fan.

Careful and detailed estimates were made of the thermal and elastic changes in diameter of the fan and of the tunnel section in the plane of the fan, and a final running clearance of 0.14 in. was adopted.

MAIN DRIVE AND CONTROL GEAR.

The fan is driven by two direct current motors, each of 2,000 h.p. mounted in tandem, and connected to the fan shaft through Bibby couplings and a carden shaft to allow for the relative movement between the tunnel and the motors, produced by the variations of temperature and pressure, to which the tunnel is subjected. Incidentally, when the tunnel is put under full pressure (4 atmospheres absolute) it increases in length by about 0.26 in. and, as this is not sufficient to cause sliding at the supports, the outer shell arches so that the ends fall. This movement is easily looked after by the Bibby couplings in the main shafting, but it is found that the couplings do not respond to the longitudinal movement, so that the rotors in the main motors are pushed along about 1/8 in. Enough clearance has been provided for this, but had the movement been greater serious difficulties would have arisen.

The driving motors are supplied by two D.C. generators coupled and driven by a common synchronous motor on the 6,600 volt A.C. mains. Ward, Leonard control is provided by adjusting the generator field and in this way, smooth variation of control can be obtained over the whole speed range.

Since the tunnel is designed to operate over a wide range of pressure, as well as speed, and since the power required by the fan will vary not only as the cube of the speed but directly as the air density, the motors and their control gear were designed to develop full power over a three to one speed range, *i.e.* from 320 r.p.m. up to 960 r.p.m. In this way the full power output of the motor is available and can be absorbed by the fan over approximately a twenty-seven to one variation of density; full power is therefore available over an operating pressure range of 4 atm. pressure down to 1/7 atm. pressure, without having to resort to any pitch changing of the fan blades.

An automatic speed control has been provided in which the voltage from a tachometer generator driven by the fan shaft is compared with a pre-set standard voltage, and the difference amplified by thyratrons is fed back to an auxiliary field in the generator.

The steady output provided by the synchronous motor, together with this additional speed control, has resulted in very constant conditions being maintained.

To take account of the variation in tunnel operating pressure, an oil seal is provided where the fan shaft passes through the tunnel shell, and the oil pressure in the seal is automatically adjusted as the air pressure in the tunnel is varied.

EVACUATION AND COMPRESSOR EQUIPMENT.

The pressure in the tunnel could be varied by two compressors, which could also be used as vacuum pumps. These compressors, each of 400 h.p. when working in parallel could raise the pressure in the tunnel to 4 atm. in about 80 minutes, or exhaust it to 1/10 of an atmosphere in 45 minutes, the capacity of the tunnel being about 125,000 cu. ft.

An 80 h.p. control unit was also provided to maintain steady conditions and deal with leakage. Provision was made for this control to be automatic, but in practice it has been found more convenient to keep the pressure constant by hand, using an adjustable air leak operated by a remote control from the observation room. The whole scheme gave rise to a complicated valve system to cover all phases of operation concerned with the pumping up or evacuation of the tunnel or the return of the tunnel to atmospheric pressure. An indicator panel was provided showing the position of all the valves, with master lights to indicate when the valve position corresponded to any condition of operation.

BUILDINGS.

The tunnel and its associated plant is housed in a reinforced concrete building. One long room houses the tunnel and to avoid heat finding its way into the tunnel, the room is lined all over with five inches of cork for heat insulation. The cork also provides effective sound-proofing, so that there is an absence of noise in the offices even when the tunnel is being run at maximum speed.

Again, to avoid heat entering the tunnel through its foundations, and at the same time to prevent the ground under the foundation freezing and disturbing the tunnel alignment, the tunnel structure is carried on large blocks formed from Foamag to provide good insulation.

Machinery rooms are located at each end of the tunnel room; one houses the main electrical equipment and the other all the ancillary equipment, such as refrigerators, condensers, evaporators, brine storage tanks, compressors and air driers.

An observation room is provided immediately to one side, and at the same level as the working section, and in this room are

grouped all the master controls required in connection with the operation of the tunnel. Under the observation room, and communicating with it by means of a lift, is a main workshop, and in front of both are offices, dark rooms, and so on, for the staff operating the tunnel.

BALANCE.

In laying out the "dead" space around the working section, deep supports were built in above the section, thus providing a rigid and level base on which to mount overhead balances and at the same time, eight supports on an independent foundation were built in below the working section, these supports being arranged to carry two beams 19 in. deep and 3 in. wide, the top of each being machined as a rail, thus providing a rigid base on which to mount a balance housed in the space below the working section.

A good deal of thought was given to various balance arrangements and in making the final choice, care was taken to leave the position as flexible as possible so as to ensure that the balance could readily be adapted to a wide range of work. Thus, in the design finally chosen, the balance was housed below the working section and consisted essentially of a framework mounted so that the vertical and horizontal forces applied to this framework could be measured and arranged so that any additional equipment could be secured to a turntable built into the top surface of the frame.

On this frame have been installed balances which measure the remaining four components, but, if necessary, these could be removed and might, for example, be replaced by a ring embracing the working section, thus adapting the balance for two-dimensional work. Furthermore, the balance has been mounted on a carriage and extension rails have been provided both fore and aft, so that, if necessary, it can easily be moved out of the way and replaced by an alternative balance similarly mounted, or the space below the tunnel left free to accept any other experimental equipment developed during the course of the work.

In the balance as originally designed, the model was mounted on thin struts fixed to the balance and passing up through the floor of the working section, the incidence being varied by raising or lowering a rear strut, which was embodied into a pitching moment balance, while the model could be yawed by turning the whole upper part of the balance.

All moving parts throughout the balance are elastically supported by flexible steel connections, single flat strip, crossed strip, or round wires being used, depending on whether the connection has to transmit a direct tension, provide a definite centre, or allow freedom of movement in more than one direction.

The forces and moments are measured by weighbeams, each with a rider weight on a lead screw and a series of drop weights by a cam. Since the balance has to be remotely controlled, it has been designed to be automatic in operation, motors being provided to drive the rider lead screw and the drop weight cam; a selsyn transmitter is coupled to each of the driving motors and this, in turn, operates a dial indicator on a balance panel in the observation room.

To provide for the automatic operation of the balance, the output of an electrical balance indicator, which operates a pointer on the balance panel showing when the weighbeam is in balance, is amplified and used to turn the lead screw in the appropriate direction so as to restore the weighbeam to its central position. When the rider reaches the end of its travel, a relay adds or removes a drop weight, thus making the balance entirely automatic.

Variable damping is provided by an oil dashpot fitted to each of the weighbeams, with a remote control adjustment and position indicator.

Details of the balance arrangements can be seen from Figs. 7 and 8. Fig. 7 shows the principle of the lift drag and pitching moment balance, and Fig. 8 how the roll, yaw and side force are measured. The drag frame is mounted on a Watt's parallel linkage and constrained to move horizontally, while the lift balance is mounted entirely on the drag frame and the pitching moment is transmitted through a parallel outer linkage to a sector member and thence to the pitching moment weighbeam on the lift frame. To measure rolling moment, yawing moment and side force, Fig. 8, each main strut carrying the model is fixed to a fore and aft member at its lower end, and the ends of these horizontal members are connected by cross frames, pivoted on a common fore and aft axis at their mid points. The two T-frames formed by the vertical and horizontal members are also linked by a horizontal cross member and the whole system, which has three degrees of freedom, is restrained by applying measured forces at the points A, B and C.

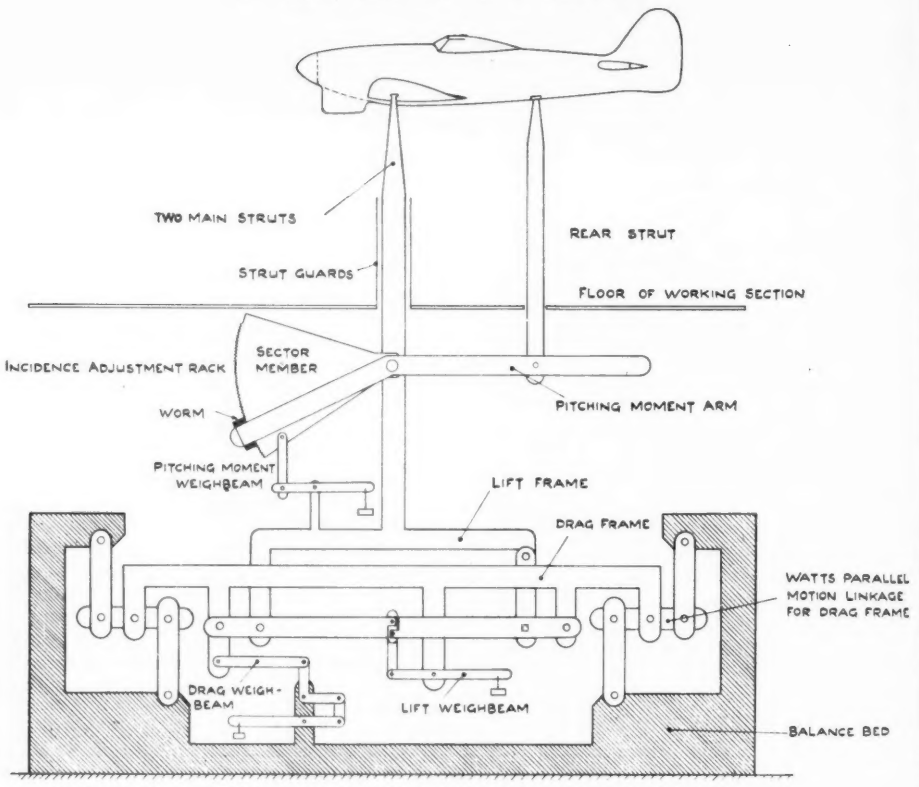


Fig. 7.
Principle of lift, drag and pitching moment balance.

The forces A and B are added together to give rolling moment, while their difference measures the yawing moment, C measures the side force.

Six weighbeams of similar design, Fig. 9. are provided and coupled through selsyns and balance indicators to dials located on the panel in the observation room. Here, together with incidence and yaw indicators and controls, they are grouped so that they can be observed and controlled by the observer; the observer waiting until conditions are steady, operates a camera which photographs a second set of dials arranged for convenience on the back of the panel. The ranges and sensitivities of the balances are: —

Lift	– 100 lb. to 1,200 lb. by 0.1 lb.
Drag	– 150 lb. to 300 lb. by 0.01 lb.
Pitching moment	±500 lb. ft. by 0.1 lb. ft.
Rolling moment	±400 lb. ft. by 0.2 lb. ft.
Yawing moment	±500 lb. ft. by 0.25 lb. ft.
Side force	±400 lb. by 0.2 lb.

SPEED MEASURING AND OTHER EQUIPMENT.

The speed of the tunnel is measured as a pressure difference between two reference holes, one in the settling chamber and the other just upstream of the working section. The pressure difference is measured on a manometric balance in the form of a weighbeam, similar in principle to main balance weighbeams.

Two cast iron pots, containing mercury and connected by a pipe, are mounted at the two ends of the weighbeam; the pots are connected to the reference holes and the pressure difference displaces the mercury from one pot into the other, thus producing a load on the

weighbeams which is balanced out by movement of a rider and drop weights in the usual way. It was found necessary to float a mixture of transformer oil and cresolic acid on the surface of the mercury, otherwise the balance had a very variable zero.

To obtain the Mach number it is also necessary to know the absolute pressure in the working section and for pressures below atmospheric, this is measured by means of a special barometer which covers a range down to 2 inches of mercury and can be read to within 0.01 inch, while for pressures above atmospheric a Bourdon type pressure gauge gives sufficient accuracy.

For general work, pressure distribution measurements, or exploration of temperatures, groups of multi-tube manometers and thermo-couple leads have been built into the tunnel, the recording equipment being located in the observation room and permanently connected to distribution boards situated in the dead space.

The manometers are filled with alcohol, the column length being 110 inches, which gives an adequate range and sensitivity for most purposes. At low tunnel pressures difficulties have been encountered because of the air which is dissolved in the alcohol coming out of the solution and tending to block the tubes. The trouble has been largely overcome by providing a vent and by using glass tubing of large enough bore to enable the bubbles to rise freely.

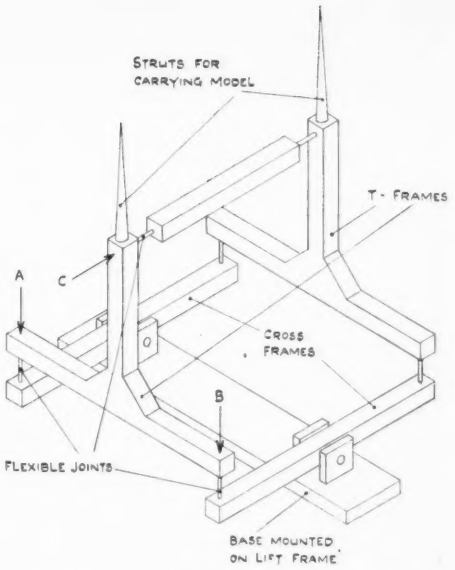


Fig. 8.
Principle of roll, yaw and side force balance.

MACH NUMBER INDICATOR.

Since the pitot pressure exceeds the static

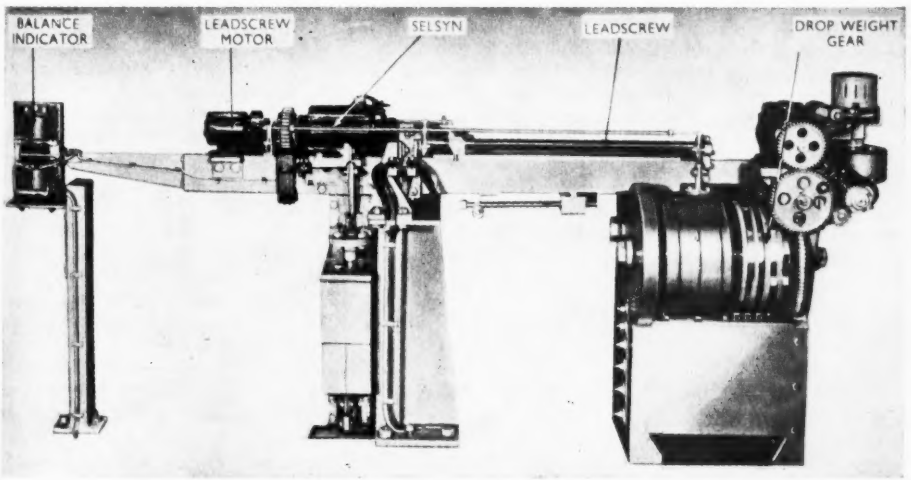


Fig. 9.
Automatic weighbeam.

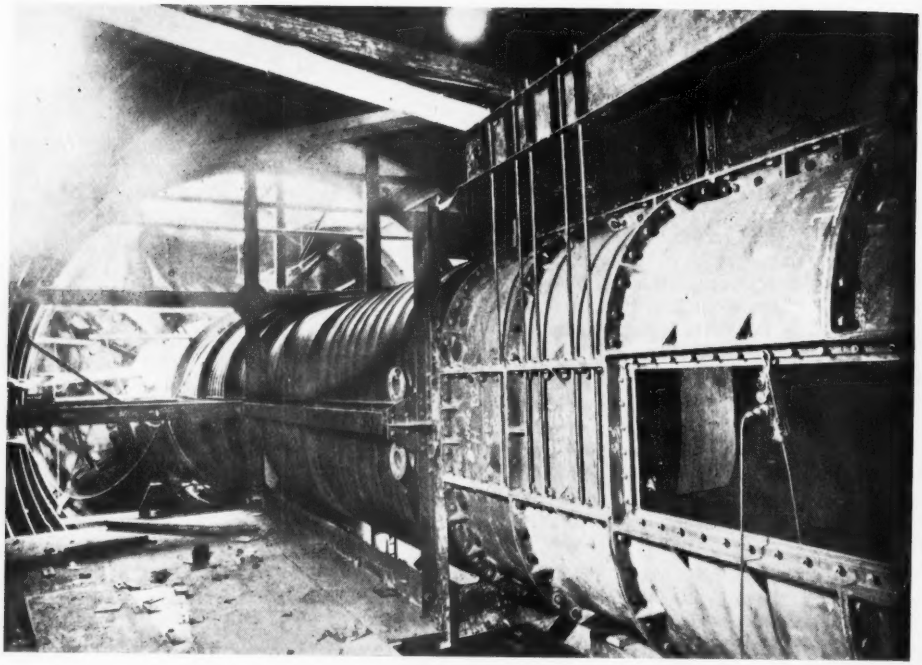


Fig. 10.
Interior view showing working section and diffuser.

by $p = \frac{1}{2}\rho V^2 f(M)$—where $f(M)$ does not differ greatly from unity and the speed of sound is given by $a^2 = \gamma p/\rho$, it appears that the Mach number V/a is approximately proportional to the square root of $\Delta p/p$. The actual expression for the Mach number is more complicated but it is still simply a function of this pressure ratio.

The Mach meter in the observation room takes advantage of this. A spot of light is thrown on a perspex screen so that its horizontal movement is controlled by Δp as given by the manometric balance and its vertical movement by the absolute pressure as given by a standard barometer used as a pressure gauge. Lines of constant Mach number on the screen then enabled the Mach number in the tunnel at any instant to be read off directly.

Figures 10 and 11 show the tunnel at various stages of construction, while Figs. 12 to 19 show some of the main items of equipment, most of which have already been described.

Figure 20 gives a general view of the tunnel on its completion in 1942 and incidentally, it also shows the 11½ ft. by 8½ ft. tunnel which was erected adjacent to the high speed tunnel and came into operation some time later.

LEAKS.

When the tunnel was first put under pressure there was a considerable leakage of air through the outer shell. This was ultimately reduced to such an extent that it could be dealt with by the 80 h.p. compressor. The effect of the leakage when the tunnel is under a vacuum may be more serious—in fact, on one occasion it caused such a rise in the humidity of the air that "rain" was produced. This was when the brine temperature had been allowed to get above 0°C., so that water which had condensed on the skin was drawn into the tunnel through the leaks. This difficulty was overcome (a) by never letting the brine temperature rise above 0°C. and (b) by installing an air-drying plant in the building housing the tunnel.

A complicated riveted structure of this type is almost impossible to seal against leaks completely. Thus the actual leakage in the high speed tunnel is around 800 cu. ft. per

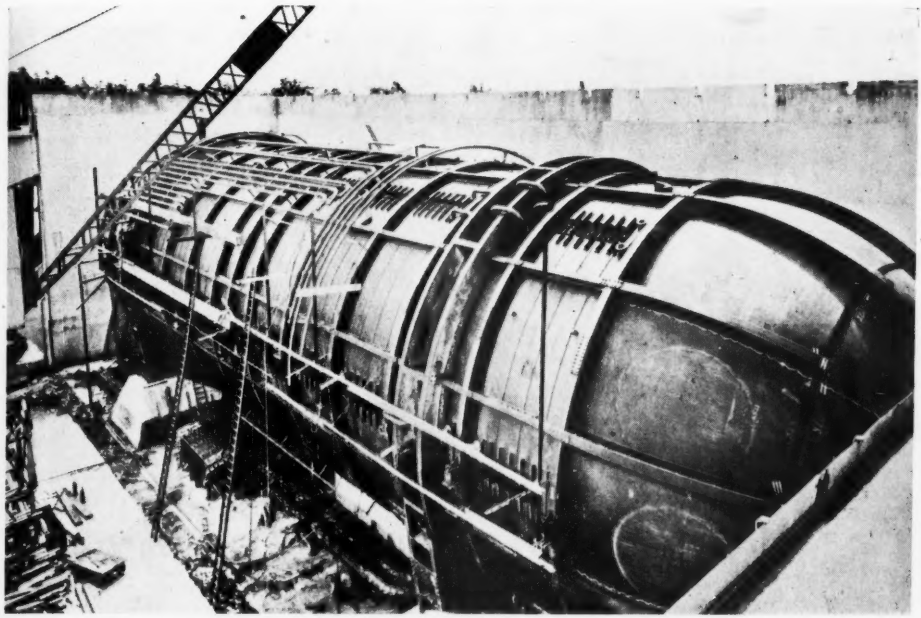


Fig. 11.
General view of tunnel under construction, July 1941.

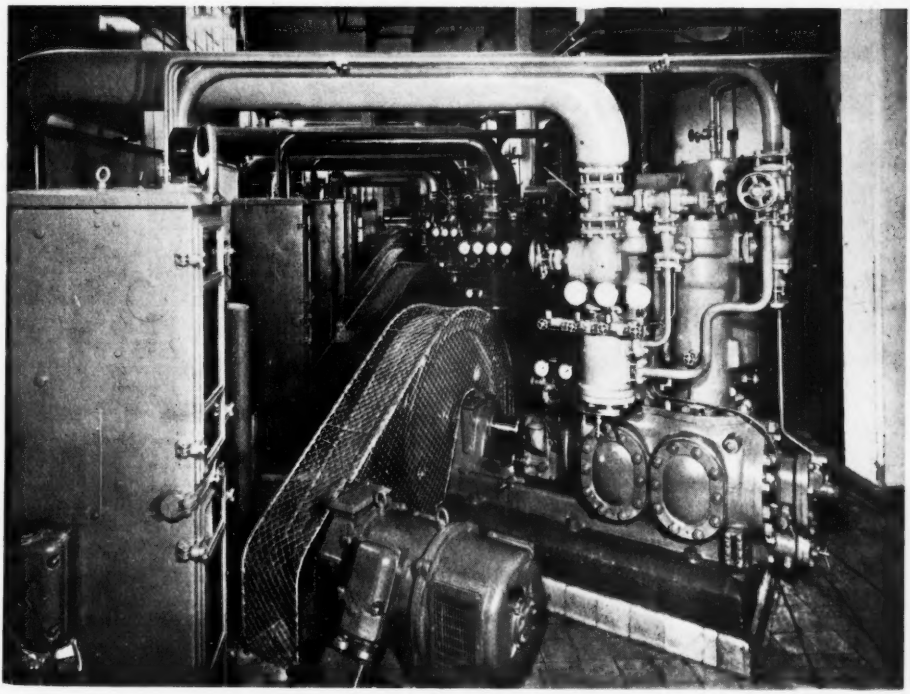


Fig. 12
Refrigerating plant.

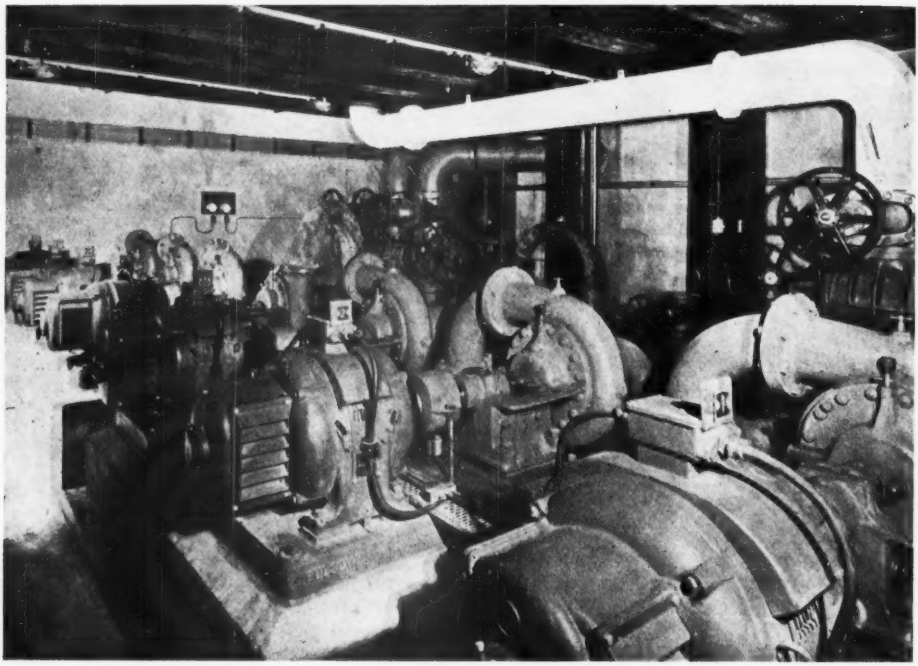


Fig. 13.
Brine circulating pumps.

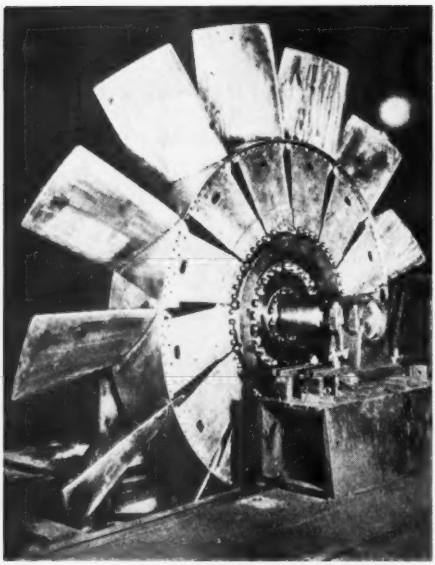


Fig. 14.
Fan showing general assembly.

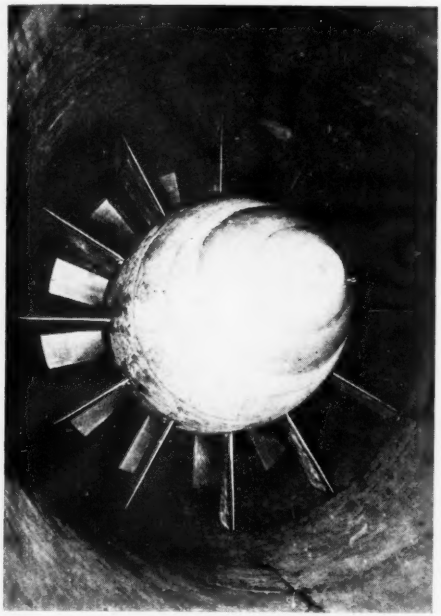


Fig. 15.
Fan in position showing pre-rotation guide vanes and spinner.

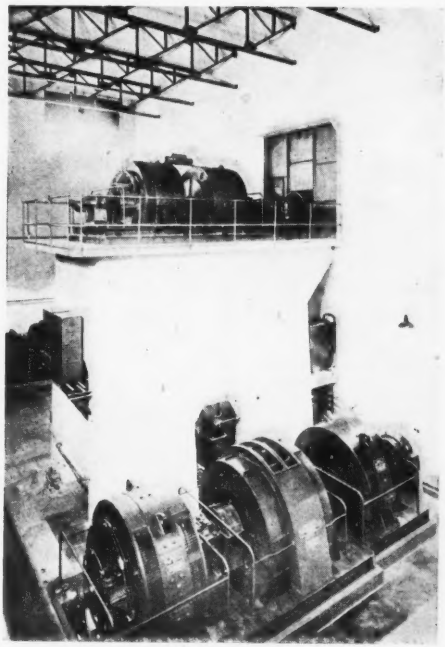


Fig. 16.
Motor generator set and main fan motors.

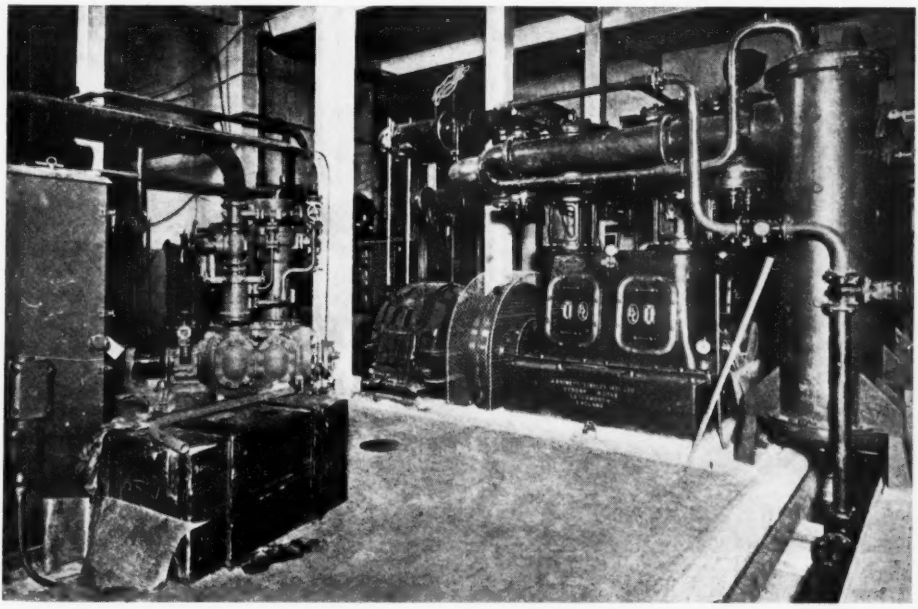


Fig. 17.
Evacuators and compressors.

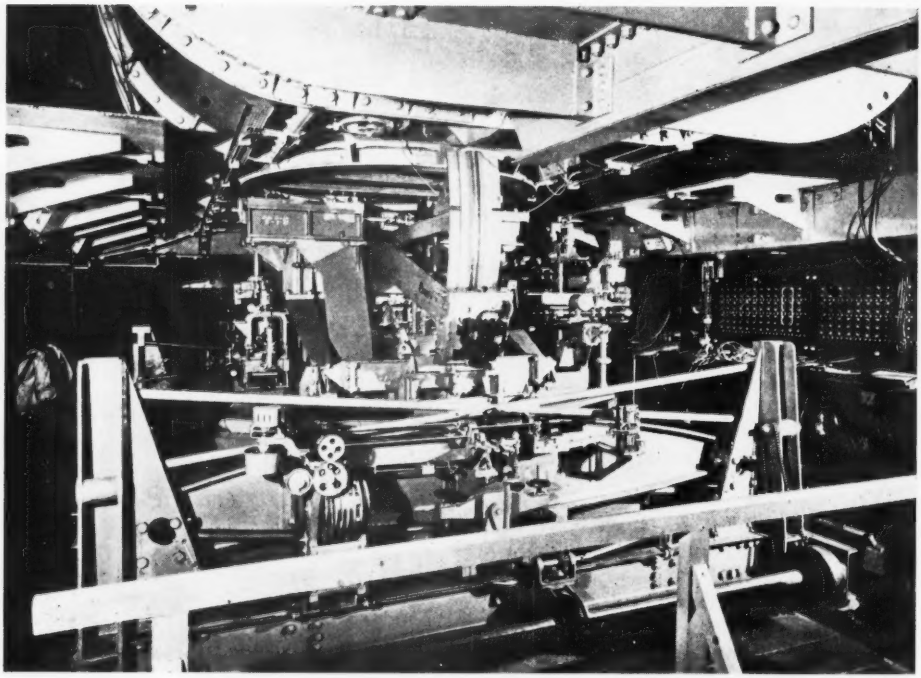


Fig.18.
General view of balance with all six components in position.

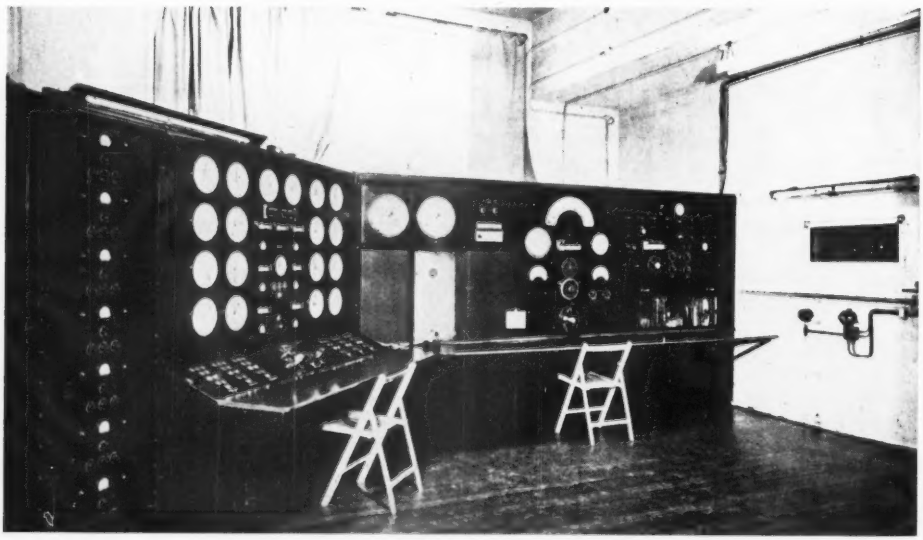


Fig. 19.
Control panel in observation room.

Fig. 20
High speed tunnel on completion, November 1942.

minute. This ought to be borne in mind when considering any scheme employing a gas other than air.

GRIT IN THE AIR STREAM.

The presence of grit in the air stream at the high speeds attained can sand-blast the model and ruin the finish of the surface. By taking great care the damage to models has been reduced to an unobjectionable amount, but there is still a certain amount of foreign matter present which, on analysis, proved to consist of sand, rust, paint, hair, cement, wool fibres, and so on. Attempts to eliminate this nuisance completely have failed so that hot-wire measurement of small scale turbulence at top speed is impossible. It seems likely that the nuisance is aggravated in a well-designed tunnel of this type, as there are no corners or pockets of dead air in which the grit can lodge.

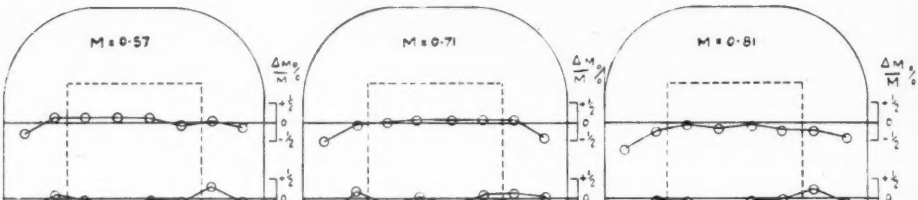
CALIBRATION OF TUNNEL VELOCITY.

It was mentioned earlier how the velocity is determined by observing pressures at two points on the tunnel wall, one in the settling chamber (p_1) and the other (p_2) just before the beginning of the working section. In deciding the position of p_2 tests were made in the model tunnel and a position was chosen which was sufficiently far upstream to be unaffected by the presence of the model. Note that p_1 and p_2 are absolute pressures.

Evidently p_1 cannot be greatly different from the total head (H_o) in the working section, and p_2 is similarly allied to the static pressure P_o. Accordingly we determine $(H_o - p_1)$ and $(p_2 - P_o)$ by calibration and render them non-dimensional by dividing by $(p_1 - p_2)$. These quantities are then functions of Mach number only (since Reynolds number has only a negligible effect) and once determined can be used to construct working calibration curves.*

To draw up these calibration curves it is necessary to have some means of measuring $H_o - P_o$ in the working section. Accordingly long pitot and static tubes were carried on the thinnest practicable steel strut extending from roof to floor. The strut could, of course, be placed in different positions, and in this way the velocity distribution throughout the working section was measured. At the highest Mach numbers this method of measuring speed was unsatisfactory, because of the choking effect of the strut, and accordingly the strut and measuring equipment were replaced by a single tube 18 ft. long. The tube was mounted on wires and projected into the working section from downstream.

*From elementary theory we have
$$H_o - P_o = \tfrac{1}{2}\rho V^2 (1 + \tfrac{1}{4}M^2 + \ldots)$$
Hence $V^2 = 2(H_o - P_o)/\rho (1 + \tfrac{1}{4}M^2 + \ldots)$
If a is the velocity of sound in the undisturbed tunnel, $a^2 = \gamma P_o/\rho$. Hence
$$M^2 = V^2/a^2 = 2(H_o - P_o)/\gamma P_o (1 + \tfrac{1}{4}M^2 \ldots)$$
so that M is simply a function of the pressure ratio $(H_o - P_o)/P_o$ and so can be expressed (graphically) as a function of $(p_1 - p_2)/p_2$.



Note:—M is the mean Mach number in the area enclosed by dotted lines and ΔM is the deviation from this mean value.

Fig. 21.

Velocity distribution across working section.

Figure 21 shows the velocity distribution at a transverse section in the plane normally occupied by the model; the general distribution is good, the deviation over the central area being well within ± 0.25 per cent.

The result of a longitudinal exploration of velocity in the working section is shown in Fig. 22. The expansion taper on the working section forms a throat at the beginning of the section. So long as the speed is everywhere subsonic the expansion over the working section results in a fall in velocity, but once sonic speed is attained at the throat the velocity downstream of the throat rises until a pressure recovery through a shock wave occurs.

Thereafter the thickening boundary layer, possibly disturbed by the change in section and the vent holes, causes a second rise in speed. Variation of the fillets, fitted into the working section, does provide a powerful method of controlling the velocity distribution and the tunnel choking and the success that has been achieved by this method will be seen later in the paper.

Interpretation of Results.

Having measured the tunnel speed and the forces, or it may be the pressures on the model, it is still necessary to determine the corrections which must be applied to these results so that they are applicable full scale. When the test has been made at a high Mach number, the power limitations on the tunnel will have restricted the Reynolds number to about one million per foot model chord, and only a direct comparison with other work, model or full scale, can give us reliable information on the effect of higher Reynolds numbers. The reduction and correction of

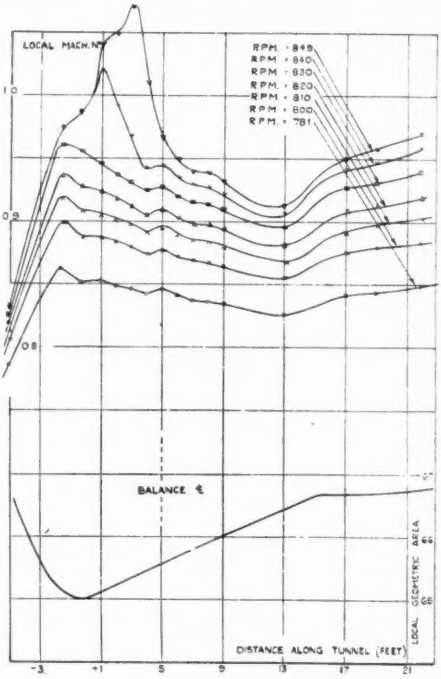


Fig. 22.

Mach number distribution in working section with original fillets. $R = 1.2 \times 10^6$ (on 1 in. chord).

the results has also presented a set of problems which are in some respects quite different from those with which we are so familiar in low speed tunnels. The additional variable, namely Mach number, not only means that the ground to be covered is enormously extended, but special difficulties present themselves and these difficulties increase as sonic speed is approached. Special methods had to be devised and it may well be that these, by presenting the subject in a new light, may affect the normal low speed tunnel procedure.

BLOCKAGE CORRECTIONS.

Shortly after the tunnel was completed, Goldstein and Young showed how the methods of applying wall corrections, which had been developed for low speed testing, could be applied to higher speeds. Their first order theory, known as the Linear Perturbation Theory, shows that the corrections normally used in low speed wind tunnels have to be multiplied by some power of $1/\beta$, where $\beta = \sqrt{(1 - M^2)}$, the power to be used for each case being specified. This is not the whole story, as is best illustrated by considering a typical drag curve as determined in the tunnel.

It is seen that above a certain Mach number (not necessarily the so-called critical Mach number dear to the mathematician's heart) the drag coefficient begins to rise rapidly. On the steep part of the curve it is evident that the accurate determination of M is all-important. By contrast this effect is very different from the usual Reynolds number (R) effect, where the quantities are so insensitive to R that it is normal to plot on log R or $1/R$ to close up the upper part of the scale. The linear perturbation theory shows that to correct the speed the factor $1/\beta^3$ should be applied to the usual blockage factor and $1/\beta^3$ becomes large as M approaches unity. This means, of course, that the blockage factor must be looked into carefully before being applied to the tunnel Mach number. Consequently, we had to reconsider and extend existing information on low speed blockage factors, particular care being given to finite wings.

A further difficulty is that the linear perturbation theory does not necessarily apply at all at these high speeds. This difficulty was brought home to us when we considered whether to use the corrected or the uncorrected Mach number for calculating β. If we used the former, we found that in some experiments the correction became indeterminate and so it was decided arbitrarily to stick to the uncorrected Mach number for the calculation of β. At the same time it was felt that this had the result of underestimating the correction, especially at the higher speeds.

The physical meaning of these difficulties will be more fully discussed later under the heading "Choking."

The type of blockage so far discussed, depended primarily on the total volume of the model and so can be regarded as the solid blockage; it is also necessary to consider the effect of the wake on wall interference.

WAKE BLOCKAGE.

The wake effects have been considered by imagining a source at the model; this source with the corresponding sink at infinity causing the same amount of outward displacement of the flow as the actual wake. This consideration showed that wake blockage could be expressed in terms of the drag coefficient, thus providing the means by which it could be evaluated.

During the investigations into blockage an alternative method suggested itself. It can be shown that the correction to, say, speed for solid blockage can be expressed as k times the percentage increment in pressure caused by the model on the adjacent part of the tunnel wall. For two-dimensional cases k is about $\frac{1}{4}$. If a similar factor could be determined for the general three-dimensional case it would provide a convenient method of determining blockage during the test itself. Experimental and theoretical work on the separation of the wake effect has proceeded a certain way, but there are obvious difficulties, all of which have not yet been overcome.

The buoyancy effects caused by the pressure gradient in the tunnel have also been investigated and were found to be small in all ordinary cases.

STRUT CORRECTIONS.

In the ordinary *ad hoc* experiments done on a complete model of a new aeroplane, the model has to be connected to the balance by struts. These are made as small as safety permits and tapered towards the top, but even so they present the greatest impediment to accurate reduction of tunnel results. They act unfavourably in two ways; first, by their

volume they add to the general blockage of the tunnel, and in this connection it is worth noting that in the case of the model it is only the images in the walls which enter into the blockage calculation, but in the case of the struts it is the struts themselves plus their images. The struts also produce at high speeds a most objectionable interference effect at the point of attachment to the wing. Elaborate tests failed to produce a general method of estimating their effect and consequently, the system was adopted of making auxiliary tests on a parallel wing. In this way, by a special rig, the effect of struts has been measured; the method neglects the effect of plan form of the wing and to a certain extent this seems permissible.

Failure to apply the corrections mentioned above results in the Mach numbers being too low, so that, for example, the drag rise appears too early. The first few reports issued in 1943 were to this extent misleading, but the methods of correction since then have been more or less standardised and are considered to be fairly reliable up to Mach numbers of 0.80 or 0.85, provided that the model span does not exceed 5 to 6 ft. To extend the tests to still higher Mach numbers, much smaller models have to be used and these possibilities and the techniques that have been employed will be discussed later in the paper.

CHOKING.

As the fan speed is increased to its maximum, an interesting phenomenon is noticed which is closely allied to that observed in a steam nozzle. Beyond a certain point the observed speed in the tunnel measured upstream of the model ceases to increase. Thereafter increasing fan speed has apparently no effect on the tunnel speed, but the drag of the model continues to rise. What has happened is this. The supersonic region on the wing has increased until it reaches well across the tunnel towards the wall. Increase of velocity through such a region causes less mass flow per square foot, instead of more. Outside the supersonic region the mass flow is still increasing, but a point comes when the two effects cancel, and no increase in mass flow as a whole results. It follows that the speed or Mach number upstream ceases to rise, but at the same time it is found that the corrected speed or the Mach number of the equivalent unbounded stream may be still increasing. It is open to argument just how far into these regions of speed it is permissible to go and still hope to attain results comparable with the free condition.

The use of a small model naturally reduces the type of wall effect considered above, but at the same time it reduces the Reynolds number and increases the difficulty of model manufacture.

The large model involves larger corrections for tunnel constraint and blockage, and until these corrections can be determined with accuracy, the smaller model is probably the better. The depression of the choking speed (uncorrected) produced by a large model, at first sight appears undesirable, but the larger the model the larger the correction, so that the loss in corrected Mach number is not so serious as the loss in choking speed suggests.

It thus appears that the worst feature of a large model is not the loss of speed but the present uncertainty of the corrections. Although theory and, in fact, common sense suggest that increasing the size of the model will ultimately cause distortion of the local flow over the surface because of the presence of the walls, the tests which we have made so far do not show any indication of this taking place. This is brought out in Fig. 23, which shows the pressure distribution over the surface of two geometrically similar aerofoils of different chord.

The form of the correction that has been applied to the observed Mach number M_u is

$$M_c = M_u + M_c\left(1 + \frac{1}{5}M_c^2\right)\left(\frac{1}{\beta^3}\right)(A + BC_D)$$

where M_c is the corrected Mach number and β as before is given by $\sqrt{(1-M^2)}$; in calculating β the corrected Mach number M_c and not M_u has been used.

A and B are coefficients dependent on the solid and wake blockages respectively.

It is seen that the agreement between the two tests is very good. This experiment formed part of a larger investigation in which three aerofoils were used, of chords 6, 15 and 37.5 inches. From detailed pressure measurements over the surfaces at various speeds and tunnel pressures, it was possible to obtain an experimental check on the methods of calculating blockage effects which has now been standardised. It appears that in these experiments it is more accurate to use the corrected Mach number in calculating β, but what is more important, it turns out that useful results can be obtained with the tunnel running in a choked condition. Thus for the higher Mach number ($M = 0.82$) shown in

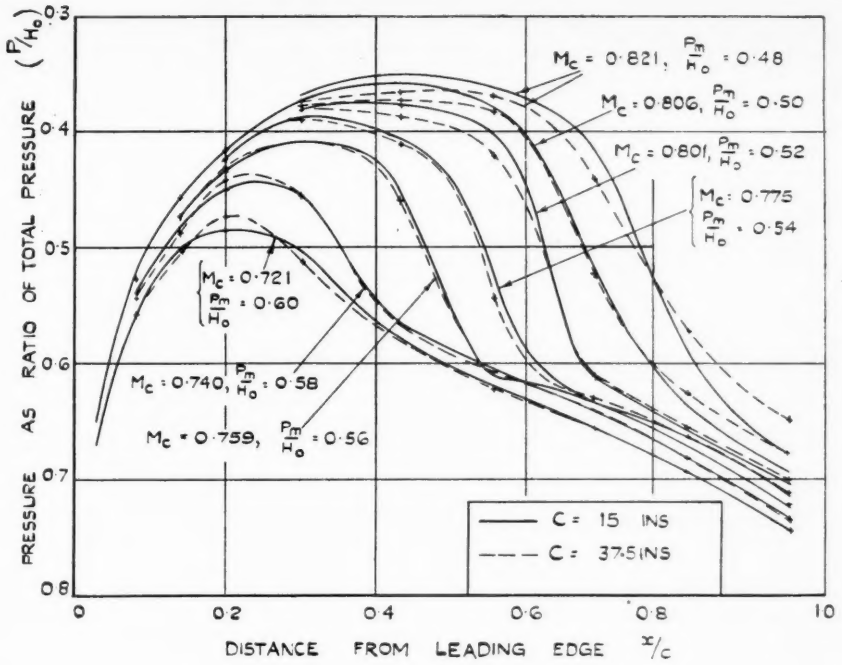


Fig. 23.

Comparison of pressure distribution on two aerofoils (NACA 0015) at the same Reynolds number. Aerofoil chords 15 in. and 37.5 in. $R = 1.4 \times 10^6$ (in the figure P_m is the average pressure on the aerofoil).

Fig. 23, the tunnel was choked with the large aerofoil but not choked for the small one. The divergencies are seen to be no larger than might be expected from experimental results on two aerofoils which, after all, may not have been exactly identical.

The results of a later experiment are shown in Fig. 24. In this case all the curves at Mach numbers of 0.82 and above were obtained with the tunnel choked, and yet there seems to be no reason to doubt that we are obtaining interesting and useful information. The progressive backward shift of the shock wave until it has reached the trailing edge is apparent. It should be pointed out that at these high speeds, since the tunnel is choked, the observed Mach number has ceased to rise, so that it can no longer be used as an indication of speed. The extensive series of tests on this aerofoil enabled a detailed analysis of the results to be made and so, by an indirect method, the corrected Mach number could be deduced.

We have not yet enough data to enable this to be done for the ordinary routine tests on a single aerofoil, but it is obviously desirable that work of this nature should continue, since ultimately it will allow us to use the tunnel well into these regions of mixed sub- and supersonic flow, where it is so necessary to obtain experimental results.

WORK OF THE HIGH SPEED TUNNEL.

The tunnel came into operation for the first time in August 1942, and the next three months were spent in balancing the fan, calibrations of the tunnel and the balance, as well as in conducting a preliminary investigation into strut interference.

Since its official opening in November 1942, the tunnel has been in continuous operation, except for a break of about one month in June 1945, when it was shut down so that the rolling, yawing and side force units could be added to the main balance, and the mixing vanes fitted to the return circuit.

During the first three years of the tunnel operation, when the work was backed by a

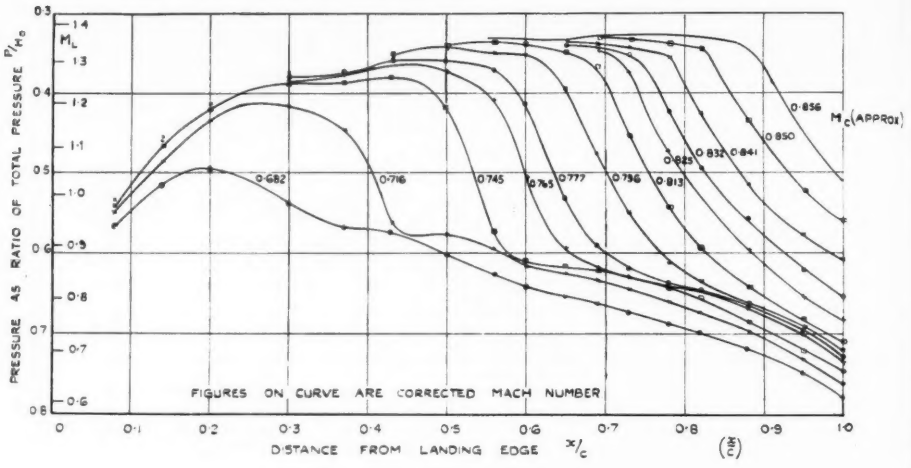


Fig. 24.

Pressure distribution on upper surface on aerofoil (NACA 0015) before and after tunnel choking occurs. $R = 2.8 \times 10^6$. Tunnel chokes at M_c of 0.82 and above.

staff of between seventy to eighty, comprising

Scientific and Technical	16
Assistants (chiefly Computors) ...	18
Designers and Draughtsmen	9
Wood and Metal workers	15
Fitters and Riggers	5
Compressor and Refrigerator staff ...	9
Electricians	3

the tunnel was run on an average between 90 to 100 hours per month, much of this running time being at full power.

It has been impossible to maintain this level of staff under peace conditions; even so, the tunnel has continued to operate at the rate of about 30 hours per month.

During its five years' running, the tunnel and equipment have performed magnificently and the tunnel has never had to shut down because of failure of any part of the plant. A good deal of the time of the tunnel, especially during the first three years of its life, has been taken up in testing complete models, and every important high speed aircraft that has been built in the country during this period, and many that were built before the period, have been tested in the tunnel. While all these tests have been valuable in their way, it has meant that a great deal of the work that has been accomplished has been *ad hoc* in character.

Reference to some of this work, and to other investigations made in the tunnel, has already been made by one of the authors in a paper presented at the Anglo-American Conference held by the Royal Aeronautical Society and the Institute of the Aeronautical Sciences in September 1947. This particular lecture discussed the effect of compressibility on lift, maximum lift, drag and pitching moment; it is not proposed, therefore, to go into these questions again in the present lecture.

Because every high speed designer is considering the consequences of sweepback, it is proposed to discuss some of the recent tunnel work on this subject and at the same time consider briefly the effect of compressibility on longitudinal stability.

Longitudinal stability and control.

The effect of compressibility on stability and control has been considered by Gates and Miss Lyon and in a generalised theory they have set out four important criteria—the static margins stick fixed and stick free, and, the manœuvre margins stick fixed and stick free.

So far, only stick fixed margins can be measured in the tunnel, the stick fixed static margin being proportional to the change in stick position required to trim in steady flight to a higher or lower speed than the initially trimmed speed, and the stick fixed manœuvre margin being proportional to the stick movement per g.

The stick fixed static margin is defined as

$$K_n = -\left(\frac{dC_m}{dC_R}\right)$$

where $C_R = \sqrt{(C_L^2 + C_D^2)}$

and in the absence of aeroelastic distortion this can be expressed

$$K_n = -\left(\frac{\partial C_m}{\partial C_R}\right)_m + \left(\frac{\gamma p M^3}{4w}\right)\left(\frac{\partial C_m}{\partial M}\right)_{c_R}$$

where p is the atmospheric pressure at the altitude under consideration,

γ is the ratio of specific heat and

w is the wing loading.

While attention to the static margin is important, what is much more important is the influence of speed on the manœuvre margin, since if the manœuvre margin becomes negative, a rapid divergence is likely to result.

The manœuvre margin is given by

$$H_m = -\left(\frac{\partial C_m}{\partial C_L}\right)_m + \left(\frac{a_1 \bar{V}}{2\mu}\right)$$

where a_1 is the slope of the tailplane lift

$$= \left(\frac{\partial C_{LT}}{\partial \alpha_T}\right)$$

$\bar{V}$ is the tail volume

and $\mu = \left(\frac{w}{g\rho l}\right)$

where as before w/g is the wing loading, and l is the tail arm of the aircraft measured from the C.G.

In considering the effect of compressibility on the manœuvre margin it is useful to consider the way compressibility affects the manœuvre point, and to do this it is convenient to express the position of the manœuvre point h_m in the form

$$h_m = h_o + (\bar{V} a_1 / a)\{1 - a(\partial\epsilon/\partial C_L) + a/2\mu\}$$

where h_o is the position of the aerodynamic centre of the aircraft less tail,

a is the lift slope of the wing and body $\left(\frac{\partial C_L}{\partial \alpha}\right)$

and ϵ is the downwash angle at the tail. Since h_o, a, a_1 and ϵ are all influenced by compressibility, and are therefore functions of Mach number, it is impossible to present a simple approach to the main problem. The problem is simplified somewhat in the case of a tailless aircraft, since we are then only concerned with h_o, *i.e.* the movement of the aerodynamic centre.

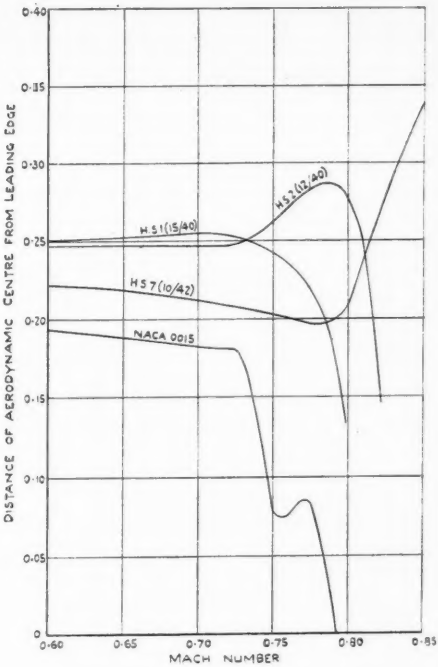


Fig. 25.

Effect of Mach number on aerodynamic centre aerofoils $C_L = 0$ to 0.1 (aspect ratio 6.0).

AERODYNAMIC CENTRE.

h_o, particularly at small angles of incidence and on conventionally shaped wings, tends to move forward as the speed increases; at first the movement is slow, but above Mach numbers of about 0.75 it can become fairly rapid. Ultimately, as the speed is further increased and becomes supersonic the aerodynamic centre moves back again and tends towards 0.5c. It is difficult to draw definite conclusions from the mass of *ad hoc* testing, and small amount of systematic work, but the general trend can be seen in Figs. 25 to 28.

Figures 25 and 26 show the effect of Mach number on aerodynamic centre for a number of aerofoils, all of aspect ratio 6.0. H.S.1 and H.S.2 have their maximum thickness at 0.4c and both are slightly cambered. H.S.1 is 15 per cent. thick and H.S.2 is 12 per cent. thick. H.S.7 is a symmetrical section 10 per cent. thick and with its maximum thickness at 0.42c; Fig. 25 also shows the results for a conventional section N.A.C.A. 0015.

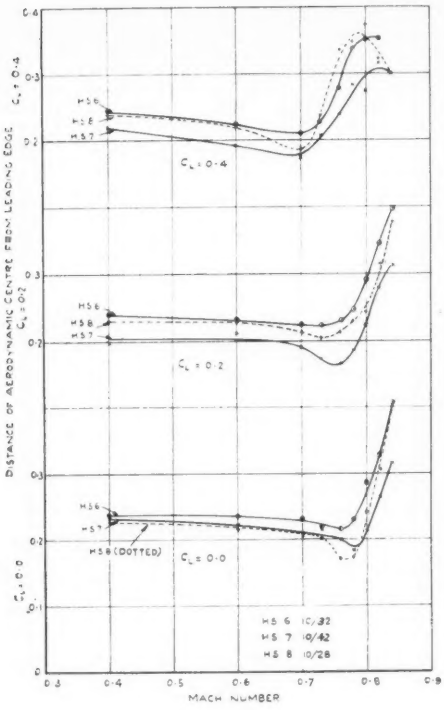


Fig. 26.

Effect of Mach number on aerodynamic centre 10 per cent. symmetrical aerofoil (aspect ratio 6.0).

All the thick sections show a rapid forward movement of aerodynamic centre at high speeds, the main movement setting in at a Mach number between 0.73 and 0.8; the thinner section, on the other hand, after showing a slight forward movement, exhibits a rapid rearward movement when the Mach number exceeds 0.8. It will be seen in a moment that this rearward movement is followed by a further forward movement (this movement coinciding with the collapse in lift), there being a final rearwards movement as the lift recovers and the Mach number approaches 0.9.

The aerodynamic centre of three symmetrical aerofoils, each 10 per cent. thick, but with their maximum thickness at 0.28c, 0.32c, and 0.42c respectively, is shown in Fig. 26. On the whole the movement in aerodynamic centre of all three aerofoils is similar; the influence of section shape, therefore, has not been very great.

The effect of aspect ratio and sweepback on aerodynamic centre is shown in Figs. 27 and 28. The results in Fig. 27 are for a wing of aspect ratio 5.8, and 14 per cent. thickness, the thickness chord ratio being measured along the wind direction. Four wings were tested, of 0°, 20°, 35° and 45° sweepback, and the position of the aerodynamic centre with respect to the mean quarter chord at three values of lift coefficient has been plotted in the figure. These results, at least up to a Mach number of 0.8, which was the extent of the speed range covered, are rather reassuring. By using smaller models, the work has now been pushed to much higher speeds and the results of some recent tests are shown in Fig. 28.

Reducing the aspect ratio has improved the characteristics, the effect of sweepback is also favourable, the curves of aerodynamic centre for swept-back wings having good characteristics up to a Mach number of about 0.85. Above a Mach number of 0.85, on both swept-back wings and delta aerofoils, the aerodynamic centre moves rapidly rearwards and in practice this will result in a large

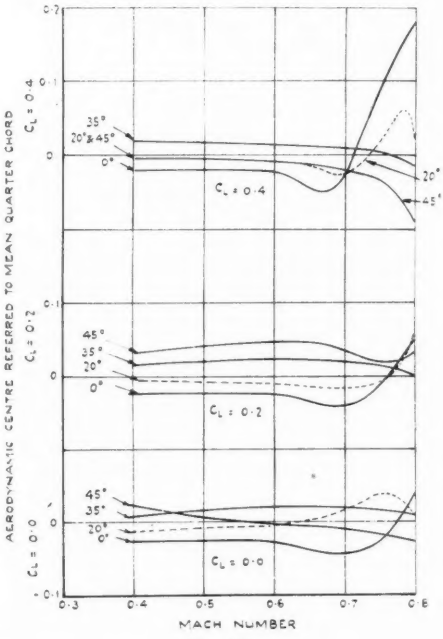
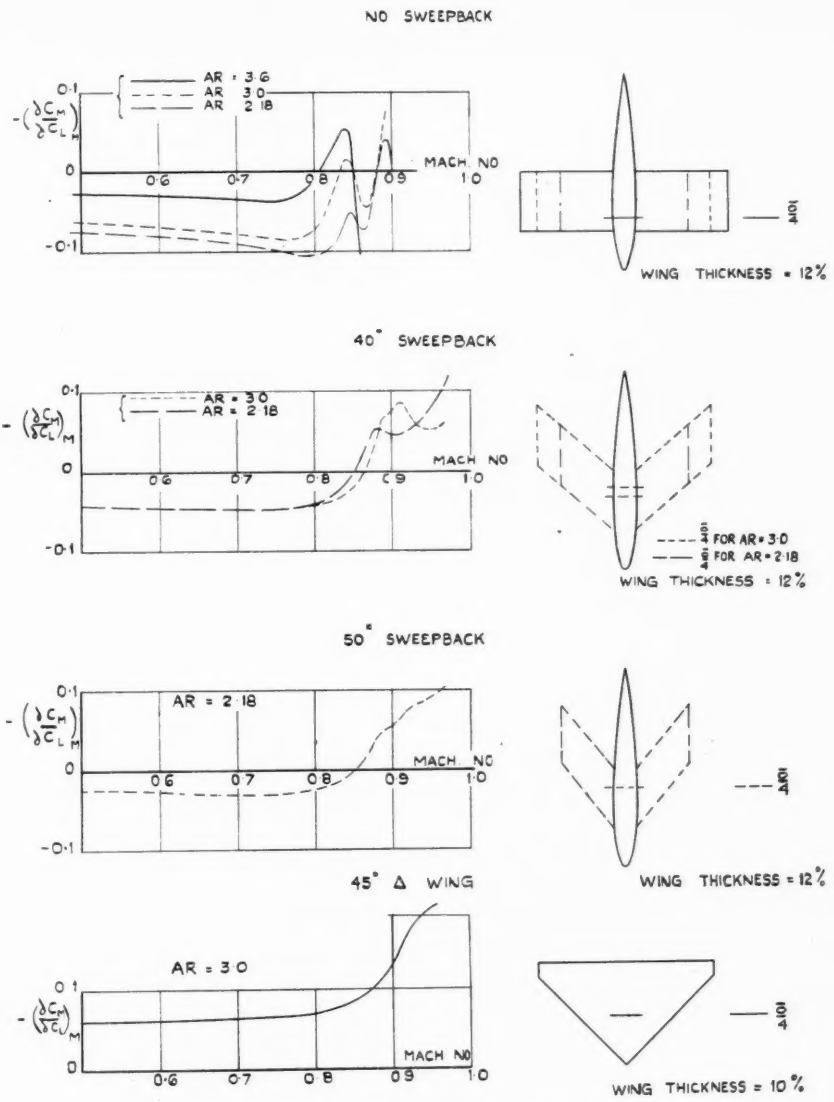


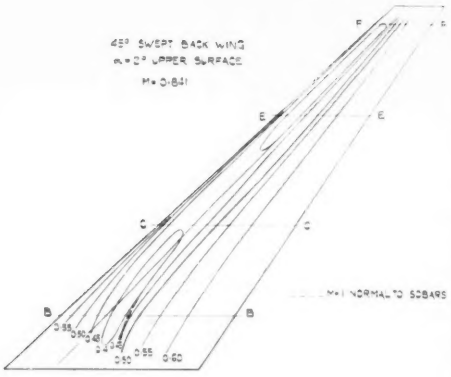
Fig. 27.

Effect of Mach number on aerodynamic centre 14 per cent symmetrical aerofoil tests on wings with sweepback (aspect ratio 5.8).



NOTE :- AERODYNAMIC CENTRES ARE MEASURED FROM MEAN QUARTER CHORD POINT. $\left(\frac{\partial C_M}{\partial C_L}\right)_M$ IS THE LOCAL VALUE AT $C_L = 0{\cdot}1$.

Fig. 28.
Effect of aspect ratio and sweepback on aerodynamic centre.



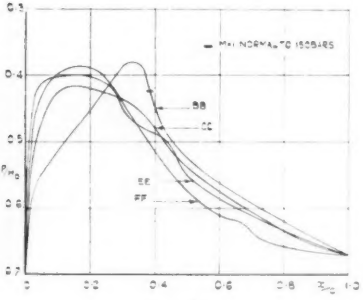


Fig. 29.
Pressure distribution on 45° swept-back wing of 14 per cent. thickness chord ratio.

increase in manœuvre margin. Such an effect need not embarrass the designer, provided that the aircraft can be kept in trim, and the controls remain effective and powerful enough to overcome this general increase in stability.

On the subject of controls, there is little we can add to the results that have already been given in the previous paper.* The further test that has been made has only confirmed the earlier work, namely elevon controls on swept-back and delta wing forms, cease to be effective at about 0.93 of the speed of sound, and at still higher speeds there is a reversal in control effectiveness.

With conventional aircraft the tail makes an important contribution to the stability and, despite the forward movement of the aerodynamic centre, tunnel tests have usually shown that the stability increases with speed.

This has been due to the fact that the contribution of the tail which is represented by

$$\bar{V}\left(\frac{a_1}{a} - a_1 \frac{\partial \varepsilon}{\partial C_L} + \frac{a_1}{2\mu}\right)$$

has offset any forward movement of the aerodynamic centre.

One of the main factors contributing to this result is the fall in a, *i.e.* $\left(\frac{\partial C_L}{\partial \alpha}\right)$, the lift slope of the main wing, compared with a_1 the tailplane lift slope.

The effect of compressibility on the lift slope was discussed in the earlier paper and the results quoted showed that all aerofoils exhibited this rapid decrease in a, at or about Mach numbers of 0.8. It is important, therefore, to examine the effect of sweepback on this result.

Flow conditions on a swept-back wing at high Mach number.

Before going on to discuss the lift slope results on wings having sweepback, it might perhaps be interesting to pause and consider the conditions of flow on swept-back wings. This has been studied by tuft experiments and pressure plotting: Figs. 29 and 30 show the pressure distribution on a symmetrical wing of 14 per cent. thickness chord ratio and 45° sweepback, the wing incidence being 2°.

The results in Fig. 29 are for a speed corresponding to a Mach number of 0.84, while those in Fig. 30 are for a Mach number of 0.9. It will be observed that the maximum suction occurs at about the semi-span and that the maximum peak suction at a section is displaced rearwards in moving from the tip to the centre section.

The effect of this displacement of the suction peak is to exaggerate the form drag over the centre section compared with the tip, where the high suction near the nose will produce a reaction in the direction of flight. This effect can be reduced or eliminated by a change in plan form or section shape, or both; moving the position of maximum thickness of the section near the root forward, for example, will correct the rearwards drift of the suction peak and should, therefore, reduce the drag.

On the plan form of the wing shown in the diagram, lines of constant pressure have been indicated and dotted lines have been drawn marking the position on the wing at which the speed normal to the pressure isobar has a local Mach number of 1.0. At 0.84 (Fig. 29)

*High Speed Performance. W. G. A. Perring. Proceedings, Anglo-American Conference, R.Ae.S., London, 1948.

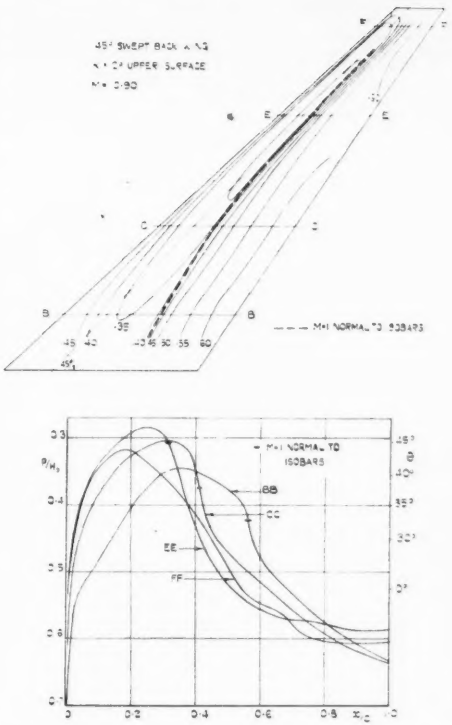
the region over which the local Mach number is 1.0 is small and is confined to an area near the root, but at 0.90 the region is large and extends nearly out to the tip. Reference to Fig. 31 shows that this line marks the boundary of an area where the surface tufts have suffered a violent change in direction. The boundary line, as was to be expected, also coincides with the point of maximum pressure recovery slope determined from the pressure distribution curves.

It is concluded, therefore, that a shock wave forms on the wing and the position of the shock is determined by the velocity normal to the pressure contour lines. It will also be observed that a local separation has occurred behind this shock wave and that the air near the surface in the region of the breakaway moves outwards towards the centre of the wing (the region of maximum suction), but at the rear of the area of separation and towards the trailing edge, the air again re-unites with the wing surface.

There is some evidence, too, of a tip stall and flow separation near the tip; this stall was, in fact, more marked in the tests at 0° incidence, when it was associated with a very violent separation starting at about 0.5c.

Flow separation behind a Mach wave has been observed during other tests and by deep tufting the area of separation has been found to extend outwards from the wing to a depth of 0.03 chords.

This correlation between the shock stall and the local speed normal to the pressure isobars, provides a very powerful method of studying compressibility and furnishes a method for determining the influence of aerofoil shape, both as regards plan form and section.



For isobars swept back at $\theta°$ the scale on the left above gives the values of $\theta°$ for a local M = 1 normal to the isobar.

Fig. 30.

Pressure distribution on 45° swept-back wing of 14 per cent. thickness chord ratio.

Effect of sweepback on lift slope at high Mach number.

Figure 32 shows the slopes of the lift curve obtained during recent tests on aerofoils of various plan forms and thicknesses. The fall in lift slope at Mach numbers of 0.8 in the case of wings without sweepback is again apparent, and it is interesting to observe that reducing the aspect ratio, while it results in reducing the slope of the lift curve at low speed, also results in a less marked collapse in lift slope at high speed.

The lift slope of swept-back wings and delta plan forms are reasonably maintained and, on the whole, improve over the range of speed it has been possible to test.

Contribution of the tail to stability.

Several factors combine which enable the tail to remain effective at high speed; first, the designer has usually chosen to make the tailplane thinner than the main wing so that the main wing will tend to "stall" earlier than the tail, the ratio a_1/a therefore increases with speed. Then again, the tailplane is in a region where the air speed due to the presence of the wing and body is less than the speed over the wing; the lower speed, while reducing tail effectiveness, also delays the onset of compressibility, thus enabling the tail to remain effective even after the wing has stalled.

Finally, there is the contribution of the downwash term

$$\bar{V}a_1\left(\frac{\partial\varepsilon}{\partial C_L}\right)$$

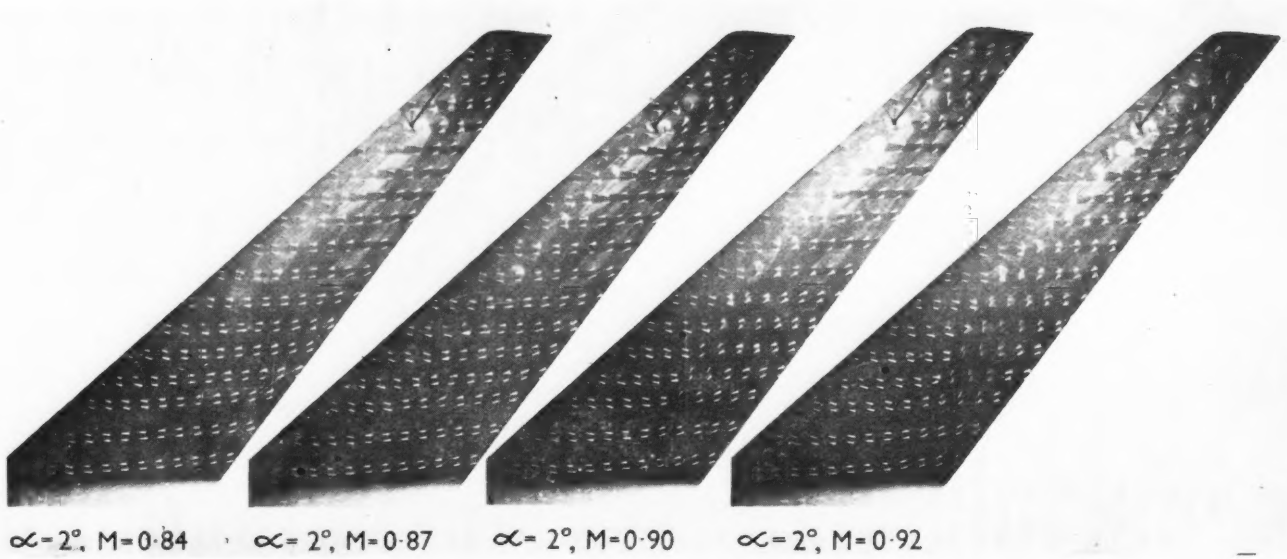
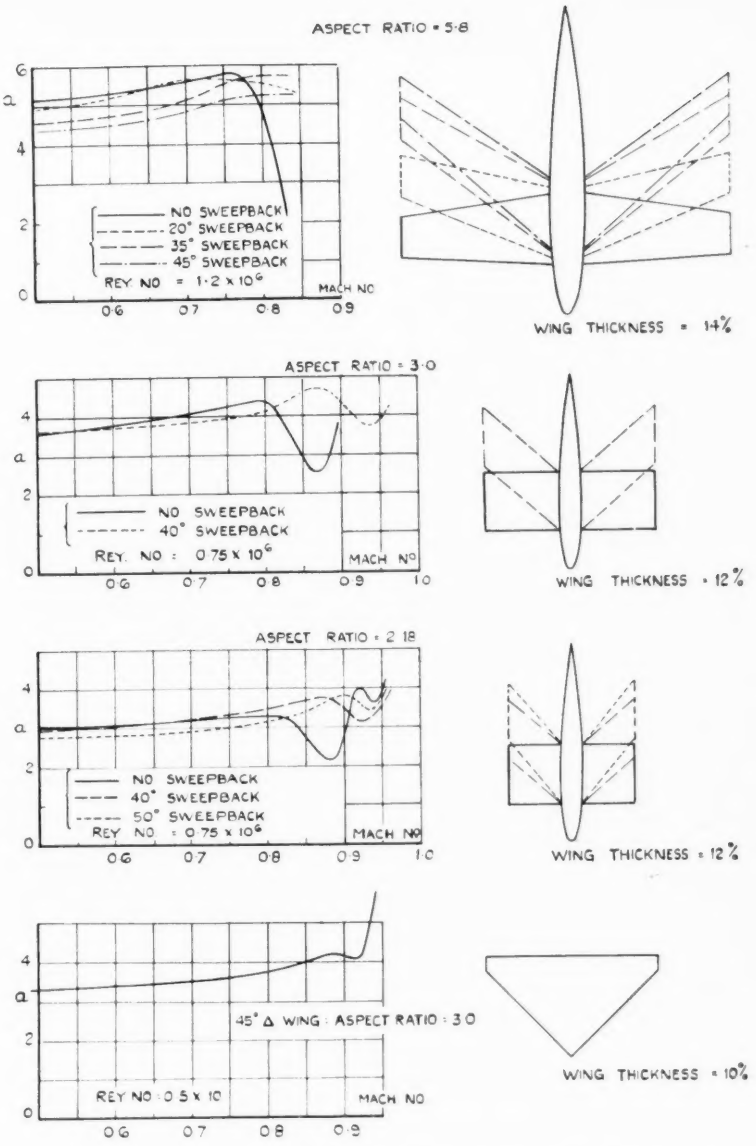


Fig. 31.
Tests on wing, 45° sweepback, 14 per cent. thickness chord ratio; flow pattern by surface tufts.



NOTE :- a (LIFT SLOPE PER RADIAN) IS THE LOCAL VALUE AT $C_L = 0{\cdot}1$.

Fig. 32.

Effect of aspect ratio and sweepback on lift curve slope.

Below speeds at which compressibility is important $\left(\frac{\partial \epsilon}{\partial C_L}\right)$ remains approximately constant, but as the speed increases there is a tendency to redistribute the lift on the mainplane, the tips taking a larger share of the lift (incidentally sweepback produces a similar result) and consequently $\left(\frac{\partial \epsilon}{\partial C_L}\right)$ will decrease as the Mach number rises. This change will again result in an increase in the tailplane contribution to the stability.

As regards the first of the factors, *i.e.* the ratio a_1/a, there is little that can be said, except to point out the desirability of continuing to make the tailplane thinner than the mainplane, and in the case of aircraft with sweepback to arrange the sweepback on the tail to be at least equal to the sweepback given to the main wings. This will ensure that the tailplane remains effective even after the flow over the wings breaks down because the second factor, namely the lower speed over the tailplane, then becomes important.

Figures 33 and 34 show some of the results of measurements that have been made in the tunnel to determine the velocity field in the wake of a wing. Fig. 33 relates to tests on a Typhoon at a wing incidence of 3.5, corresponding to a C_L of 0.4 at low speeds and to about $C_L = 0$ at a Mach number of 0.8.

The tail, although well above the wake at low speeds, moves into it at high speeds, and at a Mach number of 0.8 the mean velocity of the wake over the tail, Fig. 34, is only about 85 per cent. of the free stream velocity. While the tail effectiveness is reduced on account of the lower velocity, the effect is usually more than offset by the fact that the tail lift has been maintained by delaying compressibility.

Actually, in the case of the Typhoon, because of the rather thick tail section employed (t/c about 15.3 per cent.) a_1 the lift slope had started to fall very steeply before a Mach number of 0.8 was reached. Most aircraft models tested have shown that the tailplane lift is well maintained even with straight tails, up to a Mach number of 0.8 and above.

Before leaving the question of tailplane contribution to stability, it is perhaps necessary to say something more on the subject of downwash. On the whole $\left(\frac{\partial \epsilon}{\partial C_L}\right)$ has been found to be fairly insensitive to speed and in keeping with the redistribution of lift on the mainplane towards the tips as speed increases $\left(\frac{\partial \epsilon}{\partial C_L}\right)$ falls slightly with speed. There have been one or two exceptions to this broad rule, however, and in a few cases curves of ϵ against C_L have shown a steady increase of slope, even up to a Mach number of 0.83.

Finally, there is the term

$$\left(\frac{a_1 V}{2\mu}\right)$$

While the change in a_1 is usually small, it should be noted that μ varies inversely as density, and this leads to a slight reduction in manœuvre margin of the order of 0.02 to 0.03 at altitudes of 30,000—40,000 ft. compared with ground level.

This broad review of the factors affecting the manœuvre margin, while drawing attention to the difficulties of the situation, has offered no clear solution to the problem. There are, however, a number of hopeful signs that designers should not neglect; for example, thin wings have better characteristics than thick ones, wings of small aspect ratio behave better than wings of large aspect ratio, and wings of small aspect ratio having swept-back, or delta plan forms, do not suffer any collapse in lift curve slope, or forward movement of the aerodynamic centre, at least up to a Mach number of 0.94. As the speed approaches $M = 1.0$, there is evidence of the rearward shift of aerodynamic centre, which is to be expected as the speed becomes supersonic; powerful controls will be required under these circumstances, and some alternative to the elevon on swept-back wings or the aileron on wings without sweepback would appear to be essential.

THE PRESENT AND FUTURE WORK OF THE TUNNEL.

Over the past year or eighteen months the tunnel staff have turned their attention to the development of new techniques in the hope that it would be possible to extend the usefulness of the tunnel. From the discussion earlier in the paper, on the effect of tunnel blockage caused by the model and its supports, the importance of reducing the blockage will have become apparent.

Two methods can be employed to reduce the blockage, one the reduction in size or elimination of the model supports, and the other the reduction in the overall size of model. Both methods have been adopted and in this way, together with some redesign

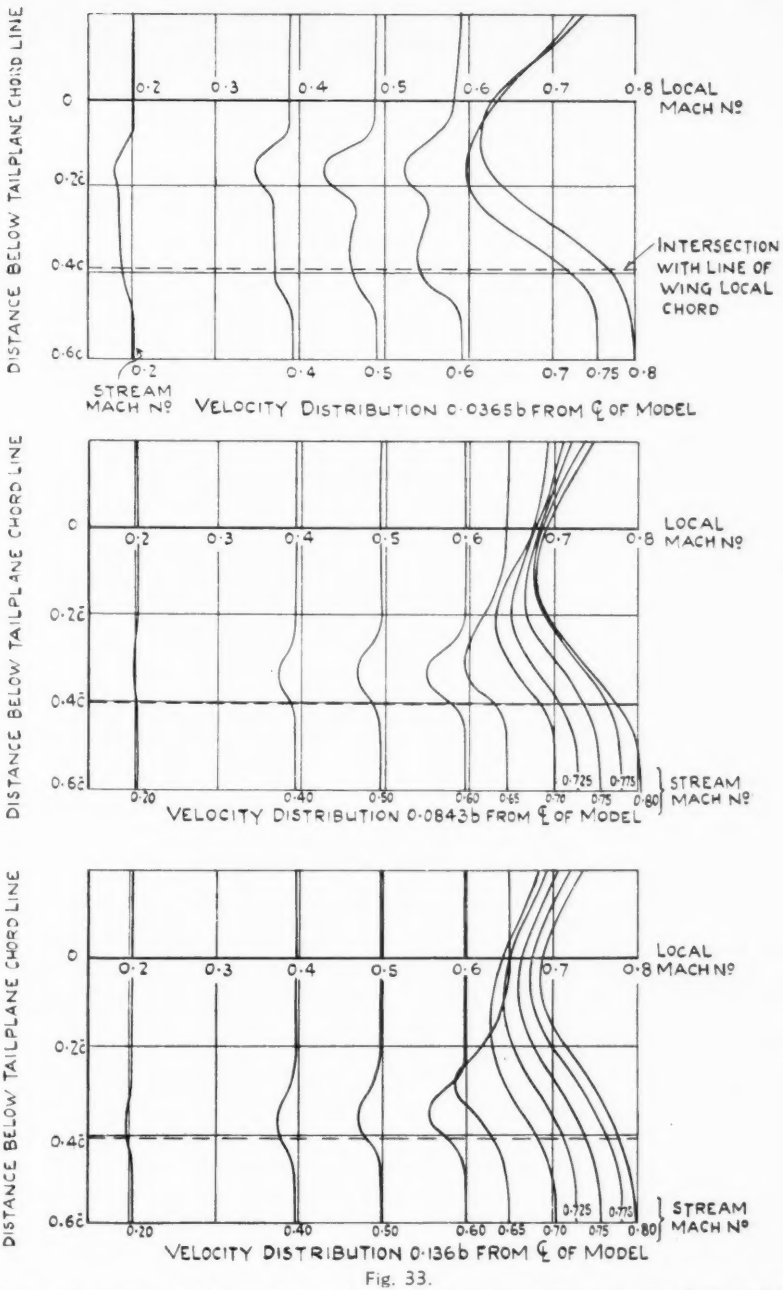


Fig. 33.

Velocity distribution behind Typhoon wing (with body in position) measured at tailplane position for wing incidence 3.5°.

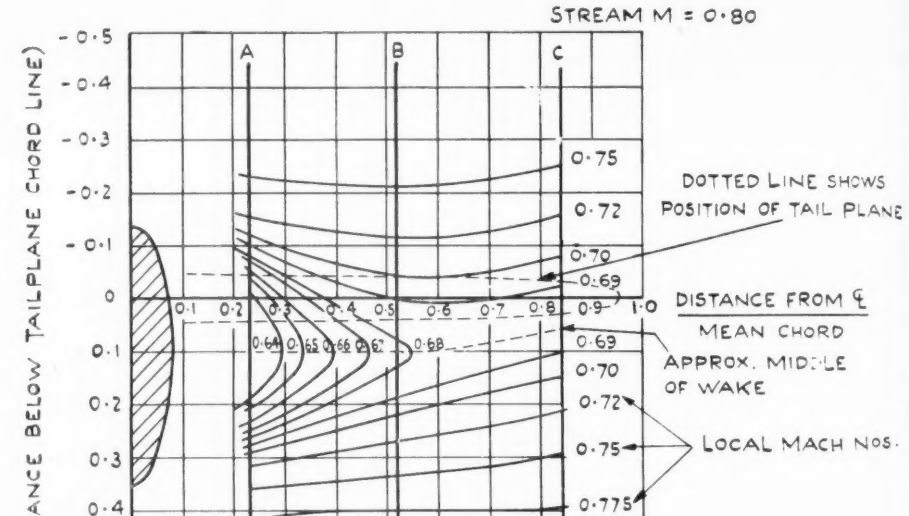


Fig. 34.
Distribution of local Mach number at position of tailplane on Typhoon
Free stream Mach number = 0.80 Wing incidence = 3.5°.

of working section fillets, it has been possible to test models over a range of Mach number up to 0. 94.

Figure 35 shows the velocity distribution along the axis of the tunnel at a series of Mach numbers from 0.83 to 0.93 deduced after making allowance for the blockage based on wall pressure measurements.

The presence of the supporting rig and the model have a considerable influence on the velocity and the tunnel fillet has to be designed to take account of the blockage caused by the introduction of the model and its supporting rig. The figure shows the velocity when the supporting rig is in position, and it also indicates the change in velocity caused by the introduction of the model.

In this work the model was supported from the rear by means of a sting (Fig. 36) and the scale of the model was adjusted so that the model span was about 2 ft. 6 in.

At the top speed of the tunnel it is possible to attain a Reynolds number of about one million, when the wing chord is 1 ft.; on this reduced size of model, therefore, provided that the model is strong enough, the Reynolds number will be about 0.5×10^6.

In the preliminary tests the lift and pitching moment were determined from strain gauge measurements made at two sections on the sting support. Two gauges were cemented to each of the upper and lower faces of the sting at station A, each pair of gauges being connected in series to one arm of a Wheatstone bridge (Fig. 37). A similar, but completely independent, circuit was used for the gauges at station B, station A and B being spaced 10 in. and 22 in. respectively from the c.g. of the model.

The sensitivity of the circuit was such that each scale division of the bridge slide wire corresponded to one cm. deflection of the galvanometer and represented a load at the c.g. of the model of about 3.5 lb.

The low humidity and constant air temperature inside the tunnel eliminated most of the troubles found in general strain gauge work, and the resulting scatter on C_m was ± 0.005 and on C_L it was ± 0.002. With a reasonably large number of readings, therefore, the overall accuracy was good.

Circuits had been arranged that enabled lift and pitching moment to be calculated electrically and the results read off directly from balance scales.

The method has now been extended to include drag; the sting is supported by means of links, so that it is free to move fore and aft, the movement being restrained by means of a spring. The displacement is measured by displacing an armature held between two opposing transformers and, at the receiving end, having an exactly similar pair of transformers and an armature which is positioned by means of a micrometer screw.

A design is now in hand to mount the sting support from the main balance, and this should improve the rigidity and make it easier to adjust the flow conditions or control the choking in the tunnel.

By these methods, and by adjustments to the working section fillets, it is hoped to extend the useful range to a Mach number of 0.96, and by further redesign of the tunnel fillets it will be possible to run the tunnel supersonically, thus extending the measurements and approaching the velocity of sound from speeds in excess of $M = 1.0$.

Attention is also being given to the development of a "half model" technique, the centre line plane of the half model coinciding either with the floor of the tunnel, or with a plate supported just above the floor of the tunnel. In this latter case the boundary air formed on the tunnel walls is by-passed below the plate and does not pass over the model.

The method has the advantage of eliminating both the interference and the blockage caused by the model supports. It also enables the model to be mounted directly from the balance, and for a given scale of model it reduces the blockage caused by the model; alternatively, for a given blockage it will permit a larger model to be used and results, therefore, in the tests being at a higher Reynolds number.

The "half model" technique is also convenient for pressure plotting work, and the results already referred to in this paper were obtained in this way.

CONCLUDING NOTE.

The authors feel in a paper of this kind that it is quite unnecessary to outline in detail the work requiring the tunnel that has still to be done.

The field of work to be covered is enormous, and this makes careful planning of the programmes of work all the more necessary.

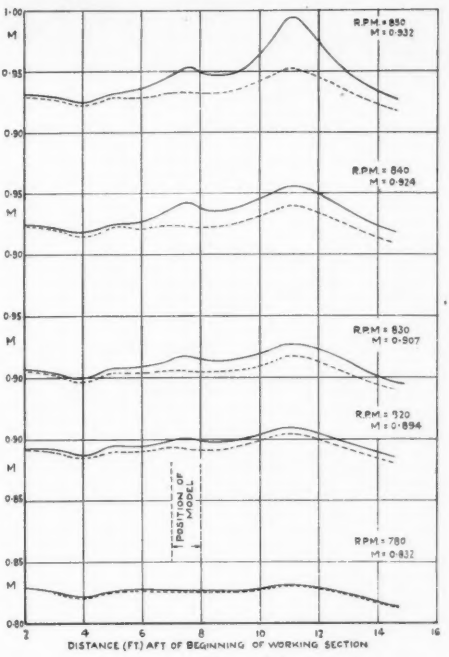


Fig. 35.
Mach number distribution along tunnel.

Aircraft development has made, and is making, such rapid progress and the high speed tunnel resources of this country are so meagre, that no effort should be spared to ensure that our present tunnel resources are run to capacity and that the country's very inadequate resources for high speed work are extended and enlarged without delay.

APPENDIX I.

ESTIMATION OF TUNNEL POWER FACTOR.

A detailed estimate of the tunnel power factor was made during 1938. In making the calculation it was assumed that the boundary layer began just downstream of the honeycomb located at the entrance of the settling chamber; it was also assumed, since at this section the velocity was small, that at this point the velocity was sensibly uniform over the cross section of the tunnel.

The power factor was found by estimating the power input at the fan necessary for the air to return to the settling chamber with the

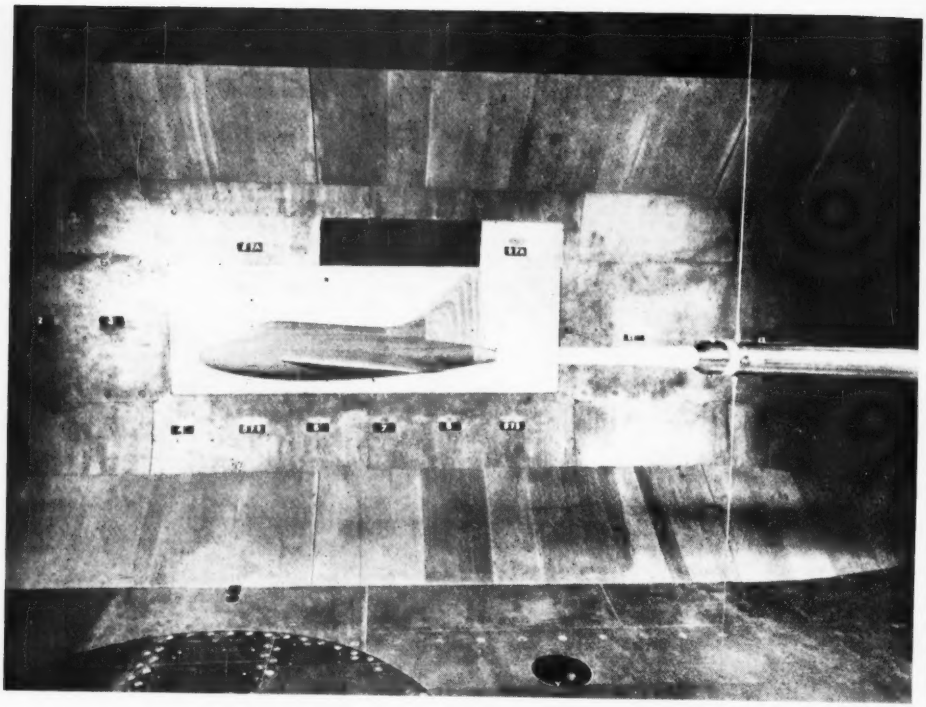


Fig. 36.
Model on sting support.

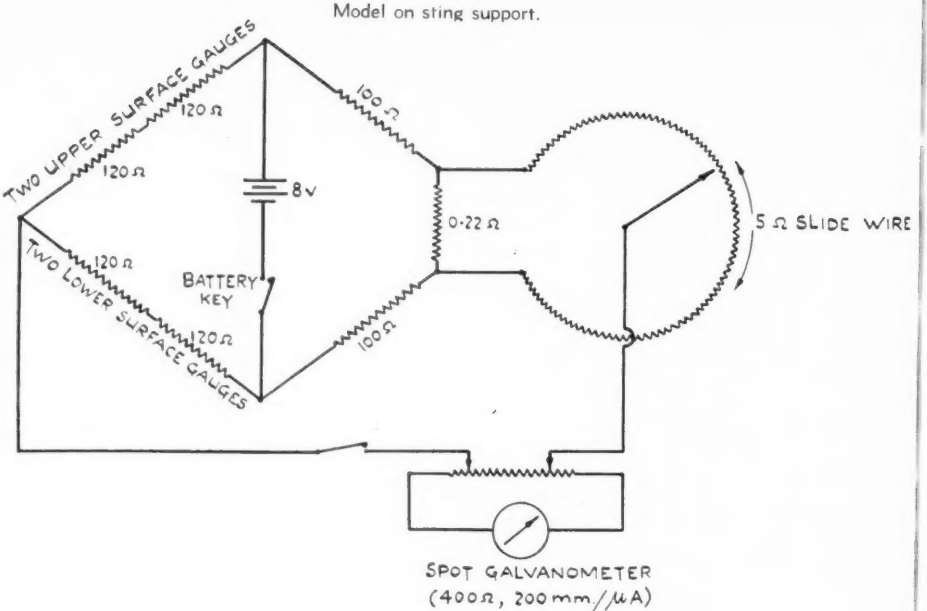


Fig. 37.
Strain gauge circuit used to measure lift and moment of model on sting support.

same pressure and velocity with which it was assumed to begin the circuit.

To simplify the calculations, all cross sections of the tunnel were assumed to be circular having perimeters equal in length to the true perimeters, but where cross sectional areas were involved in the calculations the true values of the areas were used. It was also assumed that the pressure and density across any section of the tunnel was constant, and that these were related by the law

$$\left(\frac{p}{\rho T}\right) = \text{constant.}$$

The flow over the walls was assumed to be turbulent and the momentum thickness θ, and the displacement thickness δ^* could be written

$$\theta = \int_0^\delta \left(1 + \frac{y}{r}\cos\chi\right)\frac{u}{U}\left(1 - \frac{u}{U}\right) dy$$

$$\text{and } \delta^* = \int_0^\delta \left(1 + \frac{y}{r}\cos\chi\right)\left(1 - \frac{u}{U}\right) dy,$$

where u is the velocity in the boundary layer parallel to the tunnel wall,

U is the velocity just outside the boundary layer,

y is the distance normal to the wall,

$2\pi r$ is the perimeter of the cross section of the tunnel,

and χ the angle between a generator of the tunnel wall and the axis.

If τ is the local intensity of skin friction, then the relation for a fully turbulent layer can be written

$$\frac{U\theta}{\nu} = \frac{e^{0.3914\zeta}}{4.075} = \frac{U\delta^*}{1.4\nu} \quad . \qquad (1)$$

where ν is the kinematic viscosity

and $\zeta^2 = \dfrac{\rho U^2}{\tau}$.

Substituting this relationship in the momentum equation

$$\frac{\tau}{\rho U^2} = \frac{d\theta}{ds} + \frac{1}{U}\frac{dU}{ds}(H+2)\theta$$

s being the distance along the tunnel wall

H the ratio $\dfrac{\delta^*}{\theta}$ (experiment shows that $H \simeq 1.4$)

and the momentum equation of the boundary layer reduces to

$$\zeta' + 6.13\frac{U'}{U} + 2.56\frac{r'}{r} = \frac{U}{\nu}F(\zeta) \qquad (2)$$

where the dashes denote differentiation with respect to s

and $F(\zeta) = 10.411\,\zeta^2\, e^{-0.3914\zeta}$

This equation can be solved for ζ if we know the distribution of ρ and U, which of course has also to satisfy the condition of continuity given by

$$U(A - 2\pi r\delta^*) = \text{const.}$$

Bernouilli equation

$$\frac{\gamma}{\gamma - 1}\frac{p}{\rho} + \tfrac{1}{2}U^2 = \text{const.}$$

and the adiabatic relationship referred to earlier.

A is the cross section area of the tunnel at any point.

A process of successive approximations was adopted to solve these equations; starting first with the assumption that ρ and U had the values derived by neglecting the boundary layer, the momentum equation (2) was solved for ζ.

The values of ζ were then used in equation (1) to obtain an approximate distribution of δ^* and these values were then used to obtain revised values of ρ and U.

Further successive approximations were made until values of ρ and U consistent with the above relationship were obtained.

At a point just upstream of the fan the boundary layer was found to extend to the centre of the tunnel, so that beyond this point "pipe" flow was established, and equation (2) no longer applied. Between this point and the fan the following relationship was assumed to hold

$$(p_x - p_f)\frac{(A_x + A_f)}{2} + \int_x \rho u^2 dA - \int_f \rho u^2 dA = \int_x^f \tau 2\pi r dx$$

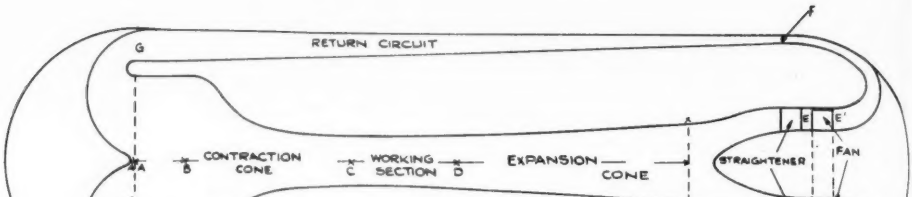
where p_x and p_f are the pressures at the start of the "pipe" flow section and the fan respectively,

A_x and A_f being the cross sectional areas, and x measures the distance along the tunnel axis.

This relation assumes that p varies linearly from section x to f, and it was solved by assuming that over the main wall, from the plane of x onwards ζ was constant and equal to 31.65. Further, it was assumed that the velocity distribution at any cross section was given by

$$1 - \frac{u}{U} = \frac{2.494}{\zeta}\log\frac{\delta}{y} .$$

The fan was designed so that the velocity



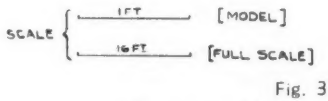


Fig. 38.
Plan view of high speed wind tunnel.

distribution just aft of the fan was similar to the velocity distribution ahead of the fan; the distribution aft of the fan, therefore, was obtained from the relationship

$$u_{f'} = k u_f$$

where $u_{f'}$ refers to the plane downstream of the fan, and k is a constant, a little less than unity, and is dependent on the power input of the fan.

In the return circuit ζ was again assumed constant and equal to 31.65 and the other assumptions made were:

(1) A 20 per cent. loss of kinetic energy at the bends downstream of the fan and at the slow speed end.

(2) After the first bend the flow was assumed symmetrical with respect to the inner and outer walls (justification of this assumption was Nippert's work on the flow in curved pipes, V.D.I. 1929).

(3) An allowance was also made for the power loss due to the honeycomb.

The flow pattern in the return circuit was calculated by working backwards from the known conditions in the settling chamber, on lines similar to that already described relating the flow at section x with section f.

The calculated distributions of p, ρ, U, and skin friction coefficient around the tunnel circuit are set out in the following table; the section references being those shown in Fig. 38.

The results relate to the 1/16 scale model, p_o, ρ_o and U_o, being the conditions at the working section, the table giving results for

$p_o = 1$ atmosphere,
$\rho_o = 0.002378$ slugs/cu. ft.,
and $U_o = 880$ ft./sec.

Position in tunnel (See Fig. 38)	p/p_o	ρ/ρ_o	U/U_o	$c_f = \frac{2\tau}{\rho_o U_o^2}$ (Inner wall)	c_f (Outer wall)	δ^* (inches) (Inner wall)	δ^* (Outer wall)
A	1.493	1.330	0.108	0		0	
B	1.493	1.330	0.108	0.00006		0.024	
C	1.000	1.000	1.000	0.00306		0.017	
D	1.000	1.000	1.000	0.00260		0.037	
X	1.300	1.205	0.595	0.00085		0.263	
E	1.343	1.235	0.452	0.00101	0.00050	0.084	0.146
E′	1.449	1.302	0.430	0.00096	0.00048	0.024	0.036
F	1.450	1.302	0.398	0.00041	0.00041	0.036	0.036
G	1.498	1.334	0.115	0.00004	0.00004	0.133	0.133
A′	1.497	1.333	0.108	0.00003		0.529	

With a fan efficiency of 88 per cent. the calculated power factor of the model tunnel was 0.21; the high speed tunnel, because of its high Reynolds number, should have a lower factor than the model, the value measured for the empty tunnel being, in fact, 0.165.

By an extension of this work into the effect of roughness the degree of permissible roughness was determined. The calculations showed that the tunnel could be regarded as aerodynamically smooth, provided that the equivalent roughness in the working section did not exceed 0.003 in. and in the return circuit 0.008 in. A ten-fold increase in equivalent roughness about these limiting values, which, of course, is not a practical figure but merely one which serves to illustrate the importance of achieving a reasonable finish, would have necessitated a 50 per cent. increase in the power requirements.

APPENDIX II.

Cooling of High Speed Tunnel.

In considering the cooling of the high speed tunnel, the rate of heat transfer through the shell to the jackets was assumed to be given by the expression

$$H = k_H \rho V \theta \quad . \quad . \quad . \quad (1)$$

where k_H is the heat transfer coefficient, ρ is the local density of the air, V the mean air velocity just outside the boundary layer, and θ is the difference between the temperature the walls would attain in the absence of heat transfer and the temperature at which they are maintained by external cooling. Since a drop of temperature of 1°C. across the walls was sufficient to allow the transfer of heat from the inside to the outside by conduction, the temperature at which the wall is maintained may be taken as 1°C. higher than the temperature of the coolant.

The equation of energy for a laminar boundary layer may be written

$$\left(\frac{D}{Dt}\right)\left[JC_pT + \frac{u^2}{2}\right] = \left(\frac{k}{\rho C_p}\right)\nabla^2\left[JC_pT + \frac{u^2\sigma}{2}\right]$$

where u is the velocity of the fluid at any point,

T the temperature of the fluid,

ρ the density,

C_p is the specific heat at constant pressure,

J the mechanical equivalent of heat,

k the conductivity of the fluid,

and $\sigma = \left(\frac{\rho C_p \nu}{k}\right)$

where ν is the kinematic viscosity.

The same equation will hold for turbulent flow, provided that the turbulence is either isotropic or fully correlated, and since it holds in these extremes it was assumed to hold in all cases.

When $\sigma = 1$, the equation can be integrated and it may be shown* that

$$JC_pT + \frac{u^2}{2} = \text{constant.}$$

The wall temperature θ_w in the absence of heat transfer, for the case when $\sigma = 1$, is therefore given by

$$JC_p\theta_w = \frac{V^2}{2} + JC_p\theta_s \quad . \quad (2)$$

where V is the velocity outside the boundary,

and θ_s is the "static" temperature.

For air σ is actually less than unity, and so, strictly speaking, the above relation will not hold, the effect of the departure of σ from unity being to lower the wall temperature slightly.

Experiment shows that the heat transfer coefficient k_H is related to the skin friction coefficient C_f by the equation

$$\left(\frac{1}{k_H}\right) = \left(\frac{2}{C_f}\right) + 5.6\,(\sigma - 1)\sqrt{\left(\frac{2}{C_f}\right)}$$

so that for air the heat transfer coefficient is slightly greater than $\frac{1}{2}C_f$.

In calculating the heat transfer to the coolant jackets, the temperature difference θ given by

$$\theta = \theta_w - \theta_c$$

was calculated, using equation (2) above, and assuming θ_c to be one degree above the coolant temperature; the heat transfer coefficients were based on the frictional coefficients obtained in making the power factor calculations described in Appendix I, and to allow for the fact that σ for air is less than unity $(\theta_w - \theta_c)$ was decreased by 2 per cent. and the heat transfer coefficient was taken to be 7 per cent. greater than $\left(\frac{C_f}{2}\right)$

The calculations made on this basis showed that a working section static temperature of 15°C. could be maintained if the mean coolant temperature of the brine circulating through the jackets was −5°C.;

*Modern Developments for Fluid Dynamics, p. 630.

the subsequent model tests, and the experience gained during the operation of the tunnel, demonstrated that the cooling arrangements were both adequate and satisfactory.

APPENDIX III.

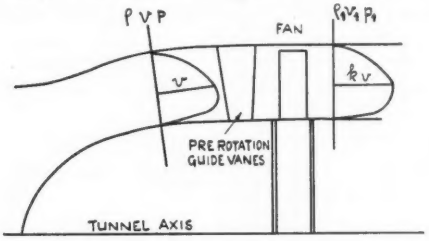
NOTES ON THE FAN DESIGN.

In deciding the fan design, the velocity distribution ahead of the fan, the air density, and the pressure, were assumed to be that given by the power factor calculations outlined in Appendix I.

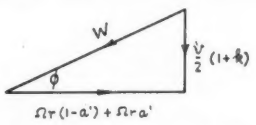
Pre-rotation guide vanes were fitted ahead of the fan and these were designed to introduce a rotation opposite in sign and equal in magnitude to one half the rotation put into the air by the fan. The fan design was arranged so that the velocity distribution at the rear of the fan was similar to the velocity distribution ahead of the fan. If v is the velocity ahead of the fan and v_1 the velocity at the rear of the fan then

$$v_1 = kv.$$

The general conditions before and aft the fan are set out in the figure.



CONDITIONS IN FRONT AND AT REAR OF FAN



VELOCITY DIAGRAM AT FAN BLADE

If profile drag losses are neglected, the following relationships will hold

$$\left(\frac{p}{\rho T}\right) = \left(\frac{p_1}{\rho_1 T_1}\right)$$

$$\int \rho v da = \int \rho_1 v_1 da$$

and $$\left(\frac{p}{\rho^\gamma}\right) = \left(\frac{p_1}{\rho^\gamma_1}\right)$$

Since, however, $v_1 = kv$

it follows $p_1 = \frac{p}{k^\gamma}$ and $\rho_1 = \frac{\rho}{k}$

The change of momentum across the fan can be written

$$(\rho_1 v_1^2 - \rho v^2) + (p_1 - p).$$

The fan thrust at any radius r can therefore be expressed

$$\frac{dT}{dr} = 2\pi r\left[\rho v^2 (k-1) + p\left(\frac{1}{k^\gamma} - 1\right)\right]$$

$$= \frac{1}{2} Bc\rho_2 \lambda_1 W^2$$

and the torque Q by the expression

$$\frac{dQ}{dr} = \frac{1}{2} Bcr\rho_2 \lambda_2 W^2,$$

where B is the number of blades,
c is the blade chord,
ρ_2 is the density of the air passing through the fan,
W is the velocity relative to the fan blade,

$$\lambda_1 = C_L \cos\phi - C_D \sin\phi$$
$$\lambda_2 = C_L \sin\phi + C_D \cos\phi.$$

By assuming the velocity through the fan to be $\frac{1}{2}(v + v_1)$ and allowing for the fact that the pre-rotation guide vanes introduce half rotation ahead of the fan, it follows

$$\tan\phi = \frac{v}{2\Omega r}(1+k)$$

and

$$W = \{\Omega^2 r^2 + v^2 (1+k^2)/4\}^{\frac{1}{2}}$$

Ω being the angular velocity of the fan.
The fan horse-power can be written

$$\left(\frac{d(HP)}{dr}\right) = \left(\frac{\Omega}{550}\right)\left(\frac{dQ}{dr}\right)$$

and if we substitute for $\left(\frac{dQ}{dr}\right)$ and eliminate Bc, by using the thrust relationship the horse-power can be expressed

$$\frac{d(HP)}{dr} = 2\pi r\,[\rho v^2 (k-1) +$$
$$p\,(1/k^\gamma - 1)]\left(\frac{\lambda_2}{\lambda_1}\right)\left(\frac{\Omega}{550}\right)$$

From energy considerations we may also write, change of total energy is

$$\tfrac{1}{2}v_1^2 - \tfrac{1}{2}v^2 + \{\gamma/(\gamma-1)\}(p_1/\rho_1 - p/\rho)$$

and it follows, therefore, the horse-power can also be expressed

$$\frac{d(HP)}{dr} = \frac{2\pi r}{550}\rho v\,[\tfrac{1}{2}v(k^2-1) +$$
$$\{\gamma/(\gamma-1)\}(p/\rho)(1/k^{\gamma-1} - 1)].$$

These two expressions for the power can be used to solve for k, and k can then be used in the blade element relationships set out above to calculate the fan details.

At the design condition of 4,000 h.p. and 600 m.p.h. air speed in the working section k was approximately 0.94 and in deciding on the fan solidity the fan sections were designed to operate at a lift coefficient of 0.5 near the tips, increasing to about 0.7 near the boss.

This loading led to blades having constant chord from boss to tip.

DISCUSSION

A. H. Hall (*Fellow*): He agreed that many more high speed tunnels were needed in this country.

At the time the tunnel was projected, the re-armament programme was in being. He paid tribute to the contractors for the energy and skill they had put into the work.

Anyone who wanted a structure such as a wind tunnel would make a great mistake in getting out the whole design in the first place. It was better to make a functional specification and to secure the advice of the contractors. This involved placing a good deal more responsibility on the engineers who were buying the materials. For instance, in connection with the structure of the wind tunnel, and so on, Mr. Perring had had to go into far more detail than would have been necessary if they had produced the design in the first place and had just asked for prices. The contractors had produced a design which was not in accordance with pre-conceived views, and therefore, it needed more investigation.

Another point was that in connection with such a job it was necessary to devise a formula whereby the Government could pay an adequate sum to the contractors for extras which could not be foreseen at the beginning.

This was not quite so easy as it appeared to be and he admitted to helping contractors in getting their claims into suitable form.

W. S. Farren (A. V. Roe & Co. Ltd., *Fellow*, formerly Director of the R.A.E.): He paid tribute to the late Mr. John Thompson, of Sir William Arrol & Co., Ltd., whose recent death had brought great sadness to all who had had the privilege of working with him. The tunnel owed more to that one man than many would ever recognise.

Undoubtedly they wanted more machinery of the kind described. Mr. Perring had been good enough to mention him by name. He had borne various degrees of responsibility for the tunnel in the years from 1936 onwards. His experience at that time had taught him that, of all the difficulties of getting such equipment, there was one of which one could fairly say that if it were overcome, everything would go forward smoothly. Those who had to foot the bill always wanted to know beforehand if those responsible for the enterprise could *guarantee* that it would do all, or even more than, they expected in their most optimistic moments, and would go on paying dividends indefinitely. The answer was almost bound to be "no," and that gave the business man the opportunity to say "You can't have it." If there was one thing that this tunnel, certainly one of the most enterprising pieces of equipment ever built in this country, could teach them, it was that if they could get good men to plan it and carry it through from the beginning, and would give them a fairly free hand in spending money, if they were prepared to trust their intuition and advice in many cases when positive proof could not be produced, and would allow them to make mistakes and to put them right, then a tunnel designed for a Mach number of, say, 0.8 on an optimistic basis could give Mach numbers of 0.9 or 0.95 ten years after it had first been conceived.

Dr. G. P. Douglas (Royal Aircraft Establishment, *Fellow*): From the beginning it had been decided that the tunnel was to be used primarily for three-dimensional research. A great deal of high speed research work could be done relatively quickly in two dimensions; but the R.A.E. tunnel was *the* tunnel in the country in which to do three-dimensional work. He believed that much of the large output from the German D.V.L. Tunnel was on a two-dimensional basis, and one might say that it was not a proper use of the equipment because this work could have been done in a much simpler tunnel.

In the Farnborough tunnel they had tested and developed the most up-to-date designs, and corresponding tests had been made in flight. Examples of this were the Typhoon and Meteor, and more recently, the D.H.108 (the Swallow). It was now appreciated that modern designs must be tested to Mach numbers up to 0.95. The final apparatus for this had only been completed and put to work a few weeks ago, but it had yielded satisfactory results from the beginning; the lecturers had shown some of the most recent results obtained with it on swept-back wings.

A. Fage (National Physical Laboratory, *Fellow*): The experience gained from the use

of the tunnel, and from the smaller wind tunnels at the N.P.L., had given them an insight into the kind of tunnel facilities that would be needed for future high speed research. Apart from tunnels exclusively devoted to supersonic research, it now appeared that the best type for general purpose research and development was a pressurised sub- and supersonic tunnel in which the model could be tested below, above, and as near as possible to, the sonic speed. Such a tunnel, having a working section 8 ft. square, had been selected for the new National Aeronautical Research Establishment at Bedford. That tunnel was urgently needed, and, indeed, was essential for aeronautical progress. The tunnel would not give them aerodynamic characteristics at Mach numbers near unity; but there were about six other techniques available which would give the information. The selection of the best techniques to use would not be an easy matter, but in any case stringent economic and financial conditions were likely to limit the choice.

A considerable part of the work undertaken in the R.A.E. high speed tunnel had been devoted to experiments on models of prototype aircraft. Such work was essential; but it must be realised that it had necessarily been done, because of limitations in trained personnel and wind tunnel facilities, at the expense of generalised research. It was not to be expected that every individual aircraft firm should, or could, provide the costly wind tunnel equipment needed to ensure the efficient design of modern aircraft, but the situation might be eased somewhat if the firms organised themselves into separate groups, each group having its own research laboratory. Such a scheme existed in America; if it were adopted in this country it would allow Government research establishments to devote far more time to the generalised basic research on which spectacular advances were likely to depend.

W. A. Mair (Manchester University, *Assoc. Fellow*): Mr. Perring had rightly paid tribute to the several firms responsible for the design and construction of the tunnel, but he did not think the tunnel would have been the success that it was from the start if Dr. Thom had not been there to ensure that everything was all right. Somehow, he seemed to be able to think of troubles before they arose, with the result that on the day on which the work in the tunnel was supposed to start, it had started. Throughout the following years Dr. Thom's enthusiasm had been so infectious that he had succeeded in getting more out of the tunnel than anyone else could have done.

Could more information be given about the long-period fluctuations which had occurred and which were investigated on the model tunnel and the experiments made in order to find a cure? This was a subject of considerable importance to others interested in the design of wind tunnels.

H. Davies (Royal Aircraft Establishment, *Assoc. Fellow*): The Reynolds numbers which could be achieved in the R.A.E. tunnel (from about half a million to two million) were rather low. Fortunately, the agreement which had been observed between the results of high speed tunnel work and of flight testing had been encouraging; in most cases the agreement had been very good. The trouble was that in the few cases where large discrepancies had occurred, they did not know whether they were due to local effects (at body or nacelle wing junctions or at the junctions of tailplane booms with wings, and so on); or whether they were due to something much more fundamental, as, for example, the inter-action of the shock wave with the boundary layer. What were the lecturers' views on that question and would they indicate what they had in mind to overcome such difficulties in the future?

D. I. Husk (Gloster Aircraft Co. Ltd., *Assoc. Fellow*): He was concerned that most of the work had been done with models. If a model turned out to be all right, they were happy, but if it did not turn out well they did not know exactly why it was wrong. Models were fairly expensive and could not easily be adjusted, and he felt that rather less time might be devoted to *ad hoc* work and rather more to fundamentals.

R. A. Shaw (National Physical Laboratory, *Assoc. Fellow*): He had recently returned from Australia and seeing this country afresh, he suggested that their biggest effort at the present time should not be towards the building of more and bigger tunnels, for the country could not afford to have redundant tunnels of that kind, but rather, that they should spend more money on the training of staff for tunnel work; the universities should be equipped with really up-to-date workmanlike plants on which people could be trained and where experi-

ments could be done on an interesting scale. He had the impression that even in such a comparatively poor country as Australia the universities were better equipped with wind tunnels than was this country. Universities should be equipped with first-class aerodynamic equipment, so that tunnels such as that described by the authors could be properly staffed and operated for 24 hours per day.

G. J. Armstrong (National Gas Turbine Establishment, *Assoc. Fellow*) *contributed*: A brief reference was made at the end of the lecture to the need for more tunnels and similarly important research facilities. They were not unaware of the general difficulties at this time but, if they were to judge by the subsequent discussion, there did not seem to be a real appreciation of the factors which were of particular significance in this connection.

Thus, despite the contrary views implied, it would seem impossible to justify large scale expenditure on the one hand for facilities for research proper and on the other hand, for similar facilities for research as applied. It had been proved recently that research and applied programmes could, in fact, exist and make rapid progress side by side within the walls of one specialised test house provided only:

(i) that they were planned well in advance
(ii) that real efforts were made to honour commitments and
(iii) that hours worked were of secondary importance to getting the job done.

In the three months beginning October the running time on the single item of major plant in this particular test house totalled 150 hours, three different full-scale compressors and one turbine being tested, each needing separate setting up and separate instrumentation. With this as an example, he saw no reason whatever why the establishments and the Industry should not get together and plan and plead jointly with added emphasis for what was so urgently required. Apart from the mutual advantage which might be expected to accrue, acceptance of this principle would lead to substantial economies in the expenditure both of money and of effort.

Again, a vital factor was time, in this instance relative and not absolute. If, realising that the pace being set by a competitor or competitors in all fields were beyond their capacity, they decided to make an effort only in a restricted field, then this effort must be a maximum: if it were useless to attempt to build *all* the research facilities needed at one and the same time, it was equally useless to attempt to build *any*, unless each was completed at a rate which was satisfying not only to those whose future usefulness to the community depended upon the possession of the facility but to those who had to create it also.

The final factor was that of responsibility for the design and construction of the facility. In the ordinary way it would be for the user to specify what he required and for the detailed layout and design to be prepared by the contractor, using such consultants as he might find essential from the structural and other points of view. But the circumstances in this case were unusual in that, as it happened, because of much past experience, the users would appear to be the best consultants also. This was fortunate and should result in a great deal of time and effort being saved, provided that the working arrangements were such as to prevent intervention by persons or bodies whose interest was either superficial or incidental. In this connection, Mr. Hall's plea that the allocation of funds to the user should not be subjected to a multitude of petty restrictions, born not of necessity but of administration, was worthy of more than ordinary attention.

MR. PERRING

Professor Thom and he appreciated all the things that had been said about the Farnborough tunnel and the way in which it was built, and he hoped the contractors, some of whom were present at the meeting, would feel that they were sharing the credit.

He agreed with Mr. Hall that to give those concerned a free hand and to trust them was a good way of ensuring that equipment would be provided quickly; he did not think there had been any serious difficulty over paying for the contract. It was estimated in 1937 that the tunnel would cost £200,000; but the war intervened, with all its attendant difficulties, and from the fact that the tunnel had cost £235,000 it was evident that the country's purse had not been stretched unduly.

Dr. Douglas had said that a great deal of time had been devoted to three-dimensional research in the tunnel. He fully appreciated the enormous amount of work involved in obtaining an understanding of the tunnel results. It was very necessary at this stage

—and here to some extent he was answering Mr. Davies—that a good deal of work should be undertaken to correlate the tunnel results with full scale; in this connection, the straightforward routine testing of large numbers of models and the comparison of the results with carefully planned full-scale work was desirable.

Nevertheless, as had been pointed out by another speaker, there was urgent need for a carefully planned systematic series of tests; the paper contained some examples of work of this kind, but much more was necessary.

He agreed entirely with Mr. Fage in advocating that future supersonic tunnels on the lines of the Farnborough tunnel should be capable of undertaking tests at high pressure and relatively low speeds, and therefore high Reynolds number, as well as high Mach number work at somewhat lower pressures. In that respect he had been guilty of ignoring the requirement put to him by his then chief, Mr. Farren, who had laid it down that they were to build a high speed tunnel. Quite early on in the consideration of the design, the possibility of combining a high Mach number tunnel with a high Reynolds number one had become apparent; this feature should be retained in future tunnels, since experience had shown it to be an extremely valuable and convenient characteristic.

As regards "scale effect" and the plans for handling work of this nature in the future, the first and most direct way was, as he had indicated, to learn by making direct comparisons between model and full scale. It had taken some 20 or 30 years to reach the present stage of understanding of low speed tunnel work, and it was encouraging to reflect that in a comparatively short time there had been built up a considerable confidence in the high speed tunnel results. He did not claim that they were in sight of the end of the road, but they had travelled a good long way along it.

The most convenient way of increasing Reynolds number in a tunnel was by increasing the working pressure, as this meant increased power. In the first of the large tunnels to be built at Bedford, the horsepower would be increased from the 4,000 available at Farnborough to between 40,000 or 50,000; a direct increase of 10 times in horse-power meant an increase of 10 times in Reynolds number, and therein lay their best hope of extending the work to higher Reynolds number.

He could not agee more with Mr. Shaw's plea for more trained staff. For some time now he had been advocating that, while an extension of tunnel facilities was essential, it was equally important that they should use to the full the facilities they already possessed. During the war the high speed tunnel at Farnborough, under the supervision of Dr. Thom, was run approximately 100 hours per month, but under present conditions, when things might perhaps have been expected to be a little easier, the tunnel was only being run about 20 hours per month. Clearly, it was important to provide more trained staff to run the tunnel to capacity; tunnels in the U.S.A. were still being run to capacity.

PROFESSOR THOM

Mr. Farren had mentioned the importance of trusting people who were doing a job and of avoiding too much criticism when they made mistakes; he remembered well that when he himself had made a bad mistake Mr. Farren was not unduly severe!

He had appreciated being chosen for the position he had filled at the R.A.E. and felt from the start that in working under Mr. Hall he was given a very free hand, a fact which had helped greatly.

He would also like to thank Mr. Mair for his remarks; success had only been made possible by the combined effort of all who worked so hard on the scheme, including Mr. Mair himself.

The question of the pulsations in the tunnel was one of general interest, the return circuit of the tunnel was annular, and it had been shown that the disturbances were periodic, causing at one instant an increase in velocity on each side, along with a decrease at top and bottom. A second or two later conditions were reversed, so that at top and bottom of the annular space the velocity was at a maximum. There were thus four nodes at the 45° points, and this suggested (since gravity could not have anything to do with it) that the phenomenon was somehow connected with the fact that the working section was rectangular. After successfully eliminating the pulsations in the model of the tunnel by inserting mixing vanes these were built into the main tunnel. This effected a partial cure and the tunnel was now much smoother in operation, but it would be interesting and useful to get to the real root of the trouble.

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DELAYS IN THE FLOW OF AIR TRAFFIC

by

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Dr. Bowen took his degree in Physics at University College, Swansea, in 1930 *and then undertook research at King's College, London. He was a member of Sir Robert Watson-Watt's original radar team in* 1935 *and served with the National Physical Laboratory and the Air Ministry. From* 1936 *to* 1940 *he was engaged on the development of airborne radar and was then attached to the Tizard Mission to the United States, spending several years on the micro-wave radar development at the M.I.T. Radiation Laboratory. In* 1944 *he was seconded to the Australian Council for Scientific and Industrial Research, to assist in radar work in the Pacific. Since* 1946 *he has been Chief of the Radiophysics Division, Council for Scientific and Industrial Research at Sydney.*

Mr. Pearcey graduated from Imperial College, London in 1940 *and from then until* 1945 *was engaged on mathematical work connected with micro-wave radar development at the Radar Research and Development Establishment at Malvern. Since then he has been in charge of the Mathematical Physics Section of the Radiophysics Division at Sydney.*

INTRODUCTION.

IT IS becoming recognised that before civil aircraft can operate at high density, the most important problem to be solved is that of traffic control. Methods exist by which a single aircraft can navigate from a distant point to an airport and let down to a safe landing under bad weather conditions. Difficulties arise when several aircraft are involved at once and long delays can occur in the neighbourhood of airports carrying high density traffic. In this paper an analysis is made of the traffic problem in an attempt to clarify some of the factors involved.

The problem has analogies with delays in telephone and telegraph traffic which have been treated extensively in the literature.[1], [2], [3], [4] The same methods are being applied to the air traffic problem in America[5] and the present study is along similar lines.

1. THE INITIAL CONDITIONS.

The problems of air traffic control fall naturally into three parts, those occurring on take-off, during *en route* navigation and in the control zone of the terminal airport. The present study is concerned only with the last of these.

The initial conditions may be specified as follows. The airport is surrounded by an area called the approach control zone (Fig. 1) within which some form of control is exercised over the movements of aircraft. The zone may be of any shape and the boundary anywhere from 5 to 50 miles from the airport, depending on circumstances. Aircraft outside the control zone are assumed to move radially towards the airport, arriving at the boundary from random directions and at random times. It is difficult at first to accept the concept of random arrivals because the movements of civil aircraft are scheduled and an effort is made to adhere to time table. An investigation of actual traffic shows that the

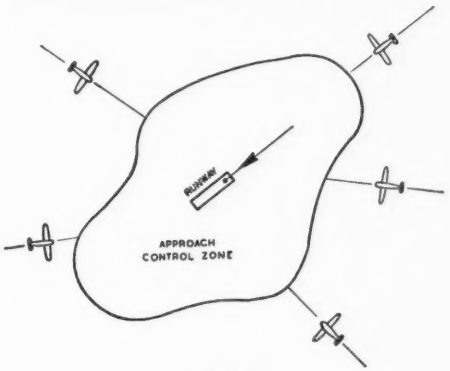

Fig. 1.
The initial conditions.

Fig. 2.
A random sequence of aircraft.

difference between the expected time of arrival and the actual time of arrival can be of the same order as the average interval between aircraft. As a result arrivals are random, from an analytical point of view, and it is shown in section 2 that this conclusion is fully justified in practice.

Aircraft make their final approach to the runway from a fixed direction determined by the wind and for safety it is necessary for them to have a certain minimum separation which is determined by the accuracy of the navigational methods in use. The safe minimum separation is usually specified as a time interval, and not a distance, and is one of the fundamental parameters in air traffic studies.

The control process is one which

(a) Transforms random arrivals into an orderly flow down the final approach path.

(b) Prevents aircraft approaching closer to one another than the stated minimum separation.

The method of control at present used under instrument conditions is to apply a holding procedure; it may be stacking in height as practised in America, the orbiting procedure of R.A.F. Transport Command, or any other. We are not concerned with the mechanism of the process but will concentrate on the more general problem.

The conditions specified above may vary considerably in practice. For example in the majority of airline operations the direction of arrival is not random, but may be limited to three or four principal directions. Or, the control zone may be divided into several parts. There may be an outer area called the Airways or Area Control Zone, and an inner one called the Approach Control Zone. Control is then exercised in two stages, an attempt being made to obtain approximate grading in the outer area and more careful grading in the inner. These alternatives make no difference to the final result and are neglected in the present analysis.

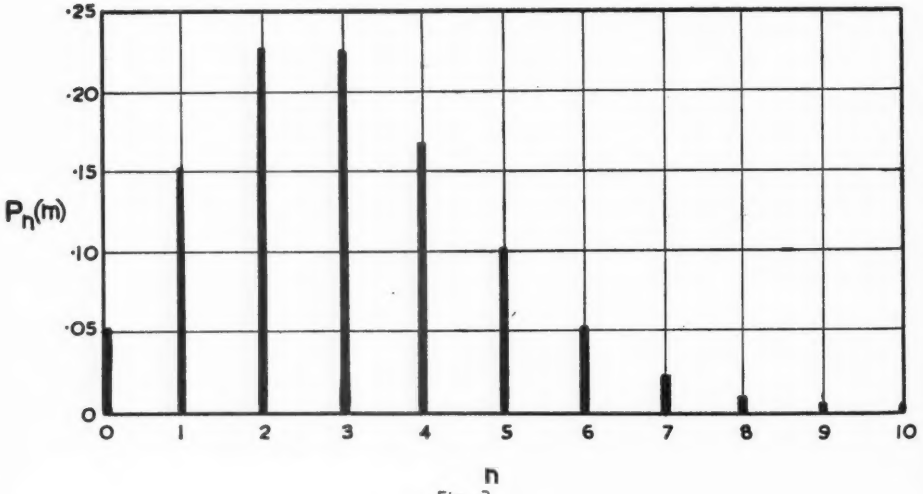

Fig. 3.
The Poisson distribution for m=3.

2. SOME PROPERTIES OF RANDOM EVENTS.

If aircraft arrive at the boundary of the control zone at random times, a plot of arrival times for a sequence of aircraft A, B, C, D and so on might appear, as in Fig. 2. For large numbers of aircraft the probability $P_n(m)$ that 1, 2 3 or n aircraft will appear in a given interval is given by the Poisson formula

$$P_n(m) = (m^n e^{-m})/n!$$

where m is the average number of aircraft arriving during the interval, and n is any integer from 0 to ∞. A curve calculated for $m=3$ is shown in Fig. 3 and, as one would expect, it has a maximum near the average rate of arrival.

The Poisson formula is the best known method of defining random events and is useful for certain types of calculation in air navigation. For example, it can be used to deduce the probable number of aircraft within a traffic control zone at any time or the probability of a radar ground beacon becoming saturated. It is not the most convenient starting point for air traffic studies, in which we have seen that the minimum tolerable separation between successive aircraft is a basic concept. The Poisson formula tells us nothing about the separation between individual aircraft and it is necessary to make a rather different approach based on the interval between successive aircraft.

If over a sufficiently long period of time the average rate of arrival of aircraft is m, the probability of one arriving between time t and $t+dt$ is mdt. The probability of no aircraft arriving in a time t is e^{-mt}. If an aircraft arrives at time $t=0$, the probability of the next one arriving between time t and $t+dt$ is then equal to

$$me^{-mt}dt$$

and for a large number of arrivals N, is

$$Nme^{-mt}dt.$$

This curve is exponential in form, as shown in the dotted line in Fig. 4 and leads to the significant result that the most probable intervals are small ones. Physically, it means that aircraft tend to appear in pairs or in groups very much more often than one would expect intuitively.

As a check that this does happen in practice, a distribution curve has been drawn for 1,254 arrivals at the Kingsford-Smith Airport, Sydney, giving the histogram plotted in Fig. 4. The average rate of arrival m was three per hour and the interval dt was three minutes. Agreement with the theoretical curve is satisfactorily close for the small number of cases considered.

The conclusions to be drawn from this curve are obvious, but very important. The first is simply that many more aircraft arrive with small separations than with, say, the average separation. The second conclusion is illustrated in Fig. 5 which gives the number of occasions per day on which aircraft are likely to arrive within 0-1, 1-2, 2-3, and so on minutes of each other, for three different rates of arrival, 3, 10 and 30 per hour. It

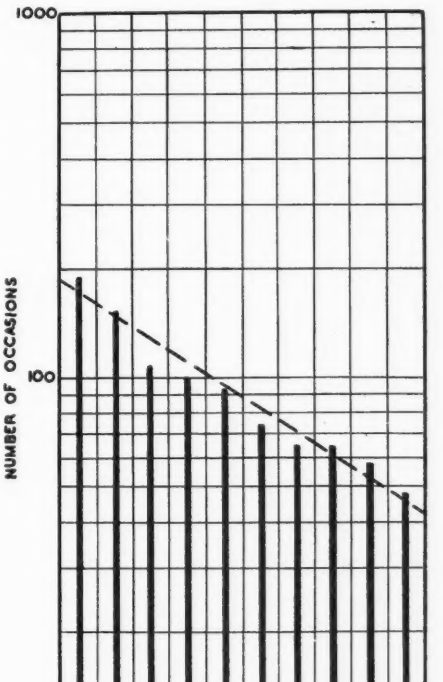

Fig. 4.

The number of occasions on which aircraft arrive at Kingsford-Smith Airport, Sydney, within intervals of 0-3, 3-6, 6-9, etc., minutes of each other. The total number of arrivals was 1,254 and the average arrival rate one in 20 minutes. The theoretical curve for random arrivals is shown dotted.

will be seen that the number of occasions per day in which aircraft arrive within 0-1 minutes of each other (Nm to a first approximation) increases as the square of the arrival rate. Thus an increase of three times in traffic density increases by nine times the number of aircraft arriving within one minute of each other. It is easy to see why the problem of air traffic control suddenly becomes critical with an apparently small increase in traffic density.

3. THE EFFECT OF A CONTROL PROCEDURE.

If aircraft arrive at random, at least some will have less than the minimum tolerable separation and it becomes necessary to perform a control operation which eliminates separations smaller than the minimum. The method used in practice is to allow the first aircraft to follow the usual approach procedure, the second one being held long enough to bring the interval up to the safe minimum separation. At high rates of arrival, the process becomes cumulative and a sequence of aircraft is held up until there is an interval long enough to absorb the accumulated delay. The process is illustrated in Fig. 6 (a) in which A, B, C, D and so on, represent aircraft arriving at random times. If the safe minimum separation is t_0, aircraft B, E, F, G and I are seen to be too close to those immediately preceding them. They are therefore delayed for a time just sufficient to give them the spacings shown in Fig. 6 (b), in which no separations are less than t_0.

It is interesting to discover what the distribution curve is for a modified sequence like that in Fig. 6 (b). An example has been calculated for 1,000 aircraft arriving at an

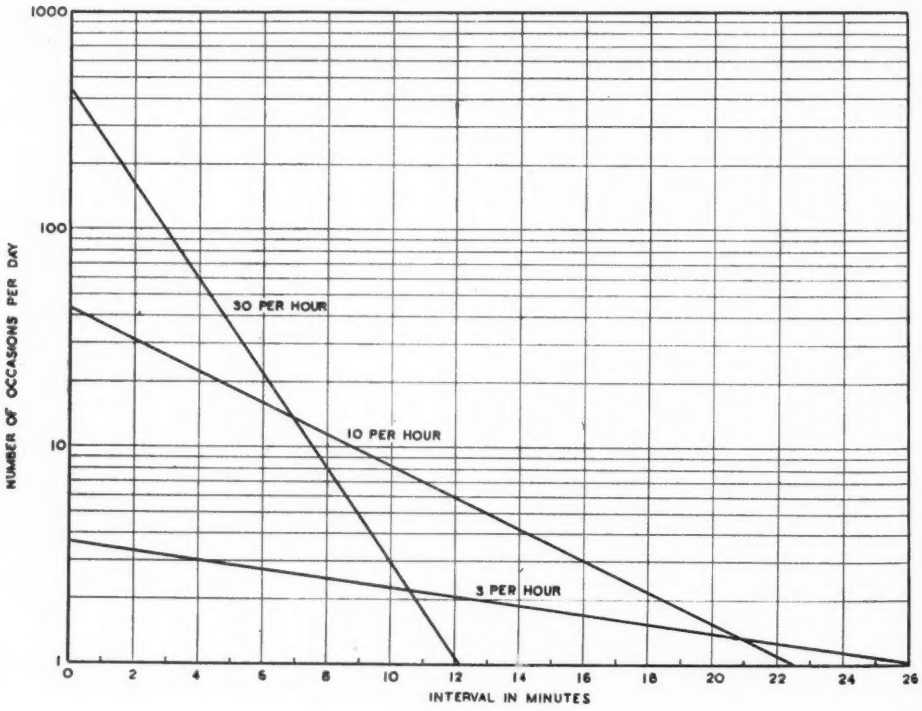

Fig. 5.

The number of occasions per day on which aircraft arrive with separations of 0-1, 1-2, 2-3, etc., minutes for average rates of arrival of 3, 10 and 30 per hour.

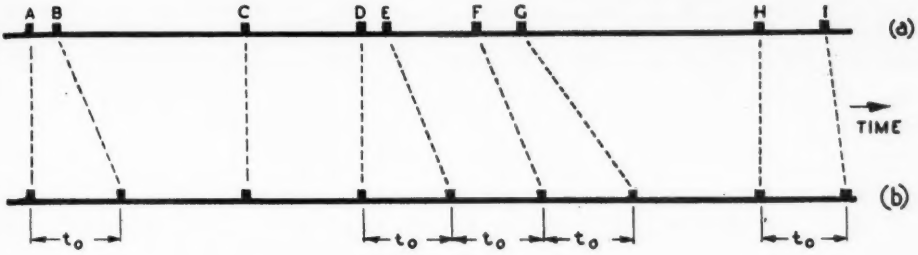

Fig. 6.

The transformation of a random sequence of aircraft into one in which no interval is smaller than t_o.

average rate of one every six minutes. For a safe minimum separation of three minutes, the new distribution has the form shown in Fig. 7. The envelope of the original distribution is shown dotted. All separations less than the minimum are eliminated and there is an increase in the number of aircraft arriving with exactly the minimum separation. In the same way, the number of longer intervals is reduced by the process. This is the distribution curve obtained as a result of applying the control procedure outlined above, and is one in which no aircraft appears with less than the minimum separation. As such, it is a safe distribution but not necessarily the best one from a traffic control point of view.

4. THE EFFECT OF A HOLDING PROCEDURE ON THE TRAFFIC FLOW.

We will now consider the effect of a holding procedure on the flow of traffic and arrive at the number of aircraft likely to be delayed under different conditions.

(*a*) *Fraction of aircraft delayed.*

It is convenient first to define a quantity T which is the ratio of arrival rate m to the maximum capacity of the airport. If the minimum separation is t_o then the maximum rate at which aircraft can land or the maximum handling capacity is $1/t_o$, and

$$T = mt_o.$$

In a sequence of aircraft arriving at random we have seen that there is a tendency for them to appear in groups, a group being defined as a series of aircraft arriving in quick succession, followed by an interval long enough to absorb the accumulated delay. In Fig. 6, for example, there are groups of two, four and two aircraft respectively. The size of these groups will vary and those containing large numbers are obviously less likely to occur than those containing small numbers. Analysis shows that the average number of aircraft in a group is equal to $1/1-T$. In any one group, all aircraft except the first will be delayed. The number delayed is therefore $(1/1-T)-1$ or $(T/1-T)$ and the fraction of all aircraft delayed is this quantity multiplied by the number of groups *i.e.* $(1-T)\,T/(1-T)=T$.

This simple result gives the fraction of aircraft delayed for different ratios of arrival

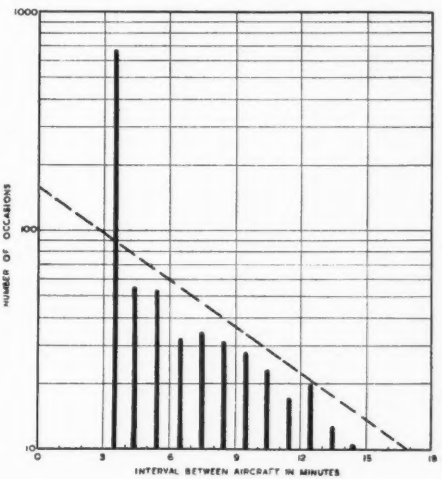

Fig. 7.

The distribution curve (full lines) obtained as a result of applying a control procedure to a random distribution.

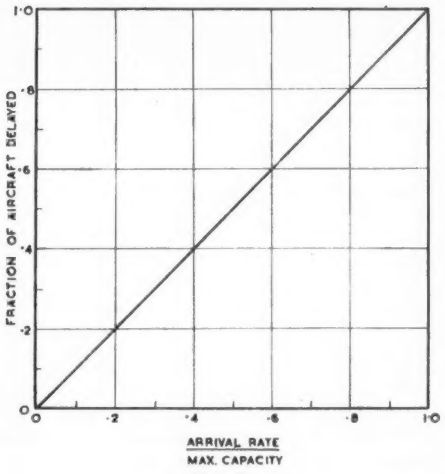

Fig. 8.

The fraction of aircraft delayed for given values of the ratio of arrival rate to maximum capacity of an airport.

rate to maximum capacity and is shown plotted in Fig. 8.

(*b*) *Average delay experienced by each aircraft.*

The next important quantity which has to be determined is the average delay experienced by aircraft in the control area. In practice, a definite amount of time is spent getting from the boundary of the control zone to the touch-down point; delay is defined as the extra time added by the control procedure.

In an average group of arrivals we have seen that the number of aircraft delayed is $T/(1-T)$. Over the interval of time occupied by a group, each aircraft on the average experiences a delay of half the minimum spacing, that is $T/2$. Hence, the average delay per aircraft in terms of their separation is

$$\tfrac{1}{2} \cdot T^2/(1-T)$$

This function is given graphically in Fig. 9 and it may be used to give the average delay in minutes for an airport of any maximum capacity or minimum separation. It is obvious from Fig. 9 that:—

(i) The delays experienced by aircraft are small only at low rates of arrival.

(ii) Aircraft are subject virtually to infinite delays when the arrival rate approaches the maximum handling capacity.

A numerical result gives an idea of the magnitude of the delays likely to occur. If the arrival rate is 0.9 times the maximum capacity of an airport, the average delay per aircraft is four times the interval between them, *i.e.* 40 minutes per aircraft if they arrive once every ten minutes.

The results reveal the simple fact that congestion at airports carrying high density traffic is a natural consequence of operating with an arrival rate too close to the maximum handling capacity and that a reasonable method of reducing the delays is to increase the maximum capacity to a figure well beyond the normal operating rate. The results are of quite general application to problems of traffic flow and may, for example, be applied to aircraft under both contact and instrument conditions. The determining factor in each case is the safe minimum separation t_o. Under instrument conditions this is large and the delays are large, but in clear weather it reduces to a small figure and the delays are correspondingly small.

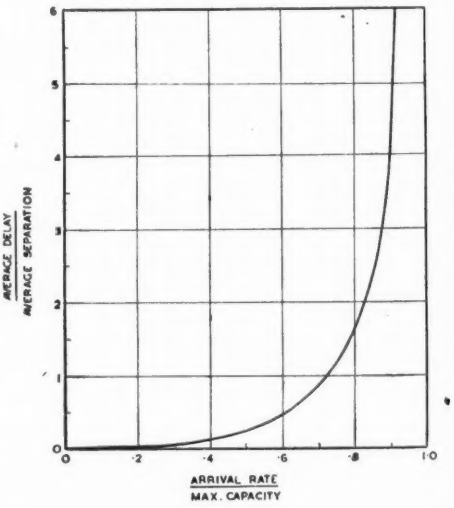

Fig. 9.

The average time delay experienced per aircraft for different values of the ratio of arrival rate to maximum capacity.

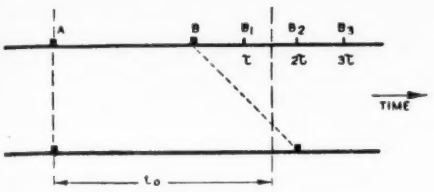

Fig. 10.

The result of finite steps in the control procedure. Aircraft B can be delayed in intervals τ to positions B_1, B_2, B_3, etc. In this example, the second aircraft would be given position B_2.

5. THE EFFECT OF FINITE STEPS IN THE HOLDING PROCEDURE.

In making the above analysis it is assumed that aircraft can be delayed by exactly the amount necessary to give them the minimum separation. In practice, fine control is not possible and aircraft are delayed in finite steps whose magnitude is determined by the kind of holding procedure employed. This is particularly true of stacking in height and of the orbiting procedure when fixed orbits are used.

The net effect is that the results given in Figs. 8 and 9 cannot be achieved by the holding procedures at present in use. If, for example, two aircraft A and B arrive with less than the minimum separation t_o, B can be held for period τ, 2τ, 3τ and so on, corresponding to positions B_1, B_2, B_3, etc., in Fig. 10. In this example, position B_2 would be chosen and the delay experienced would be longer than necessary. The final effect has been derived by numerical computation for values of τ which are respectively 1/10 and 1/6 of the minimum separation. The results are given in Figs. 11 and 12. It is seen that the number of aircraft delayed is little affected by finite steps in the control procedure. The effect on average delay (Fig. 12) is serious, however, particularly at high rates of arrival when the delays tend to become infinite before the maximum capacity is reached.

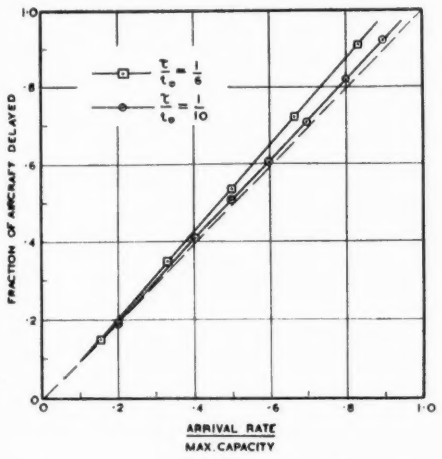

Fig. 11.

The fraction of aircraft delayed for different values of τ/t_o. The curve for infinitesimal values of τ is shown dotted.

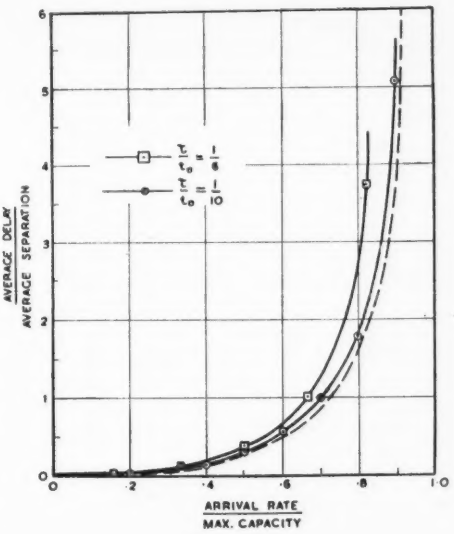

Fig. 12.

The average time delay per aircraft for different values of τ/t_o. The curve for infinitesimal values of τ is shown dotted.

This result lends even greater emphasis to the previous conclusion that the rate of arrival must be kept small compared with the capacity of an airport. It also brings out an important requirement in the control system—that a holding procedure must be capable of fine control over the movement of aircraft. A fair approximation to optimum conditions is obtained when the ratio τ/t_o is of the order of 1/10. In an airport expecting to handle aircraft at a rate of one every five minutes, therefore, the holding procedure needs to be adjustable in steps of 30 seconds or less.

6. CONCLUSION.

This analysis brings out the fact that any attempt to operate an airport near its maximum capacity results in long delays and an accumulation of aircraft waiting to land. There has been a tendency in the past to assume that the maximum capacity of an airport is the working capacity and to design airports and their facilities accordingly. This is a mistaken conception. It appears that the only practicable method of operating without serious delays is to provide a large reserve capacity, or else to work with a safe minimum separation which is small compared with the average interval between aircraft. The implications are serious and need careful consideration from nearly every aspect of traffic handling—the design of navigational aids, airports and of aircraft themselves.

This work is part of the programme of the Council for Scientific and Industrial Research, Division of Radiophysics, Commonwealth of Australia. A full mathematical treatment of the problem will be given in a subsequent paper. The authors wish to acknowledge with thanks the help received from other members of the staff of the laboratory and from officers of the Australian Department of Civil Aviation.

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REVIEWS

The Science and Engineering of Nuclear Power. Various Authors. Edited by Clark Goodman. Addison-Wesley Press Inc., Cambridge, Massachusetts, 1947. $7.50.

This is a remarkable book, remarkable not only for its subject matter, but also for the way the book is produced.

First as to subject matter. This is to explain the fundamental bases of atomic energy in terms which will be easily understood by engineers. That is an object of the highest value. The scientific investigation of the structure of matter, in all its stages, chemical and physical, has ultimately required the understanding of the engineer and the practical business man, before the results of the investigations can be fully applied for the benefit or destruction of mankind.

The Nuclear Power Engineering Society has yet to be founded. Whether it will be or not will depend largely upon whether we spell it Democracy or Democrazy. But in either event the Atomic Energy Engineer is being trained and this type of book will be one of his text books.

Chapter I deals with the Fundamentals of Nuclear Physics, Chapter II with the Fission Process, and so through the various chapters on Pile Theory and Control and Operation of the Pile to Nuclear Fuels.

Valuable and comprehensive though the information contained in the book under review is, it has still to be translated into more engineering terms than at present. So much of the information has been obtained and presented by pure scientists, simply because the atomic energy engineer has not yet come into his own. The present book is a splendid beginning, and beautifully produced, but there is much yet to be done. The Massachusetts Institute of Technology, largely responsible for the contents of this volume, which contains the essentials of a series of seminars initiated by it, is to be congratulated and one looks forward to the second volume now in preparation.

An Introduction to Aerodynamic Compressibility. J. Black. Bunhill Publications Ltd. 1947. 18/- net.

This monograph gives a survey of the considerable amount of work, spread over a wide range of books, journals and reports, which has already been done on compressible flow. It will be of great interest to those whose work is connected with problems of the dynamics of gases even in fields of application outside aeronautical engineering.

However, it is doubted whether the student or the practical engineer without a thorough scientific background will gain much without referring to the original papers or the funda-

mental theories. In such an attempt, the extensive references given in the book will be most helpful. As a whole, present knowledge of compressible flow is well represented and so is the supersonic field We would, however, like to see references made in this type of book to more practical up-to-date problems of aeronautical engineering; for instance, the drag characteristics of wedge sections in the trans- and subsonic region, of modern high speed sections beyond the critical Mach number, and of conventional streamline bodies and shells in the subsonic, trans-sonic and supersonic regions.

Although the book would be more valuable if it had more individuality, it is a useful contribution to this latest field of development and research.

AN APPRECIATION

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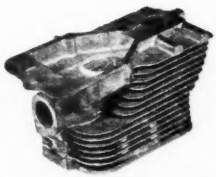

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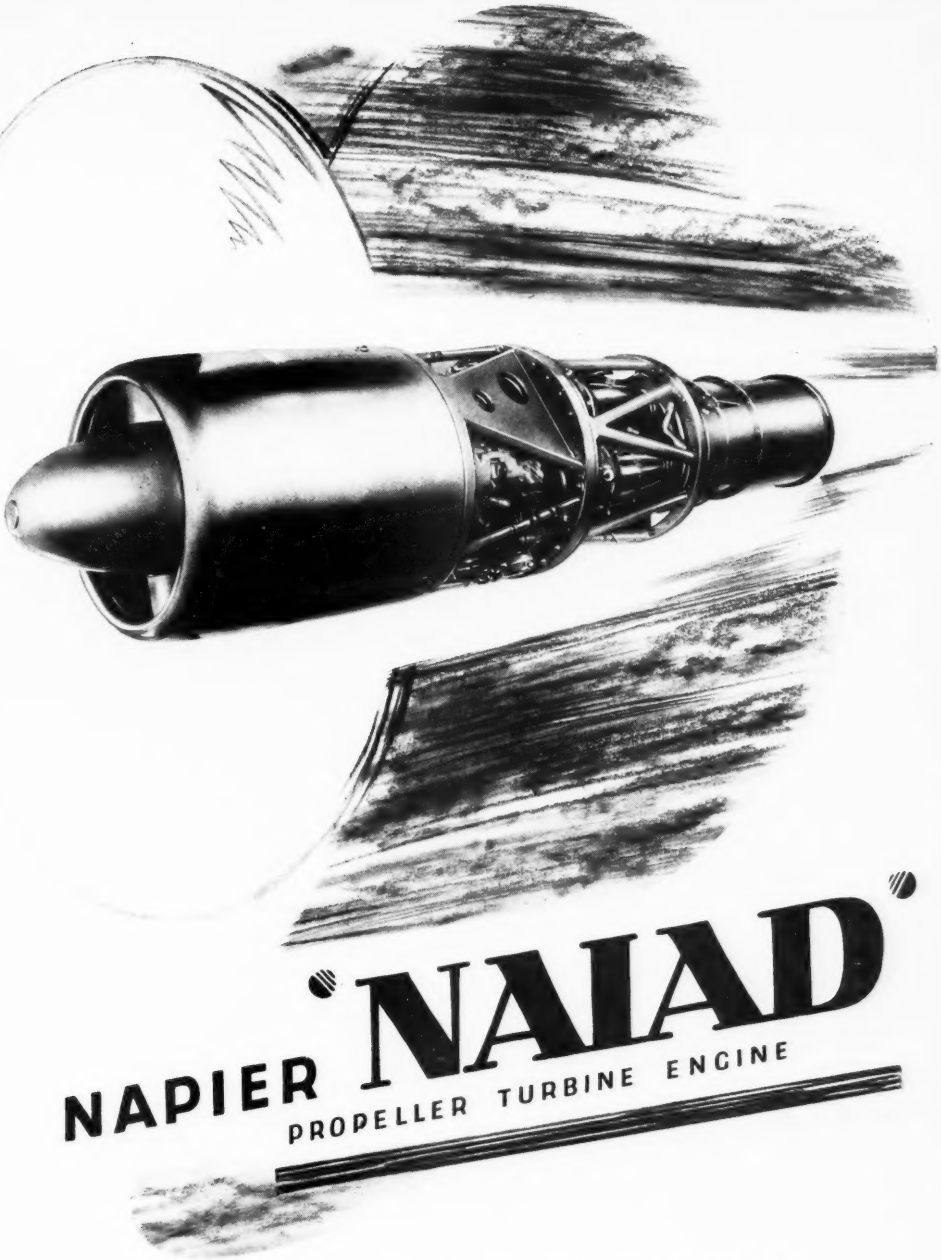

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